AGARD-AR-360 Vol. III

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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD ADVISORY REPORT 360

Aerospace 2020

(Aéronautique et espace à l'horizon 2020)

Volume III — Background Papers

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

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Foreword

Change is affecting every aspect of our lives, and the pace of change is accelerating. In an effort to forecast where the forces of change will lead NATO and its member Nations over the next quarter century, the NATO Advisory Group for Aerospace Research and Development (AGARD) commissioned the *Aerospace 2020* study.

The study attempts to strike a balance between possibility and promise. Some discussions are undoubtedly too conservative while others too optimistic. In any case, *Aerospace 2020* attempts to identify methods and processess that will help the Alliance and the Nations benefit from the opportunities, and prepare for the possible dangers, which change inevitably creates.

The study involved virtually all of the AGARD organisation, capatalising, in particular, on the strengths of its seven Technical Panels composed of experts in fields ranging from aerospace medicine to fluid dynamics. The study also tapped the military expertise of representatives from AGARD's Aerospace Applications Studies Committee and the information management skills of the Technical Information Committee. Consistent with the nature and philosophy of AGARD, each of these participants expanded the network of professionals to include views and opinions of civilian and military experts from industry, government and academia.

We wish to take this opportunity to thank all of the people who contributed to the *Aerospace 2020* study and assisted in its preparation and production. Special thanks are extended to Dr. Hywel Davies, rapporteur; to Lt. Col. John Wheatley, study executive; and to Jürgen Wild, Director of AGARD, and his staff.

As AGARD evolves into NATO's new Research and Technology Organisation, it will retain its spirit of service to the Alliance, of international cooperation and of dedicated professionalism. It is in keeping with this spirit that *Aerospace 2020* is presented, and we hope the study will prove valuable to NATO and its members as plans, preparations, and decisions are made for our entry into the 21st century.

Avant-propos

Le changement a des répercussions sur tous les aspects de notre vie, et son rythme s'accélère. Afin de prévoir jusqu'où l'OTAN et ses pays membres seront conduits par les forces du changement au cours des prochaines vingt cinq années, le Groupe consultatif pour la recherche et les réalisations aérospatiales de l'OTAN (AGARD) a lancé l'étude "Aéronautique et espace à l'horizon 2020".

L'étude tente de trouver un juste équilibre entre les possibilités et les potentialités. Certains des débats qu'elle contient sont, sans doute, soit trop conservateurs, soit trop optimistes. Quoiqu'il en soit, "Aéronautique et espace à l'horizon 2020" tente d'identifier les méthodes et les processus qui permettront à l'Alliance et aux Nations de profiter des possibilités offertes et de se prémunir contre les dangers potentiels qui sont la conséquence inévitable de tout changement.

L'étude a bénéficié de la participation de la quasi-totalité de la structure AGARD, tout en tirant parti des connaissances de ses propres Panels techniques, composés d'experts dans tous les domaines aéronautiques, allant de la médecine aérospatiale à la dynamique des fluides. L'étude a également fait appel aux compétences techniques militaires des membres du Comité des études en vue d'applications aérospatiales de l'AGARD, ainsi que le savoir faire en gestion de l'information de son Comité d'information technique. Conformément à la nature et à la philosophie de l'AGARD, chacun des participants a cherché à élargir son réseau de professionnels pour y inclure les avis et les opinions d'experts civils et militaires travaillant dans l'industrie, dans l'administration et aux universités.

Nous saisissons cette occasion pour remercier tous ceux qui ont contribué à la réalisation de l'étude "Aéronautique et espace à l'horizon 2020". En particulier, nous tenons à exprimer nos plus vifs remerciements au Docteur Hywel Davies, rapporteur; au Lt. Col. John Wheatley, administrateur responsable de l'étude; et à Jürgen Wild, le Directeur de l'AGARD, et son personnel.

En évoluant vers la nouvelle Organisation OTAN de Recherche et Technologie, l'AGARD continuera à apporter à l'Alliance sa volonté de servir, son esprit de coopération internationale et sa vocation professionnelle. C'est dans cet esprit que l'étude "Aéronautique et espace à l'horizon 2020" est présentée. Nous espérons qu'elle s'avérera utile pour l'OTAN et ses pays membres, pour les plans, les préparatifs et les décisions prises en vue de notre entrée dans le 21ième siècle.

Michael I. Yarymovych
Chairman of AGARD

Nils Holme
Study Director
Aerospace 2020

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Aerospace Medical Panel

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Drawing On Today's Wise Investments: Longitudinal And Baseline Human-Resource Research

R.E. King
S.E. McGlohn
P.D. Retzlaff

Summary: Many of the pilots who will be flying in the year 2020 are just now being born or are currently very young children. We will know more about these pilots than we presently know about our current pilots. The air forces of the future will surely include many more women as they will likely compete on an equal footing and may be represented in all cockpits. Efforts currently underway, including *Neuropsychiatrically Enhanced Flight Screening*, *Assessment of Psychological Factors in Aviators* and *Psychological Factors of Aviators' Success* may bear fruit and answer the question of whether female pilots self-select into aviation *or* if they are shaped as a result of the process of pilot training. The year 2020 may see the *Armstrong Laboratory Aviator Personality Survey* as a well established test for use with aviators, with international norms. As we invest increasingly large amounts of money into each individual airframe and mission, we must learn more about the human operator, whether that individual is a pilot or a controller of a pilotless aircraft or spacecraft (Uninhabited Aerial Vehicle).

Introduction: The human side of the man-machine equation is currently considered the more unknowable, despite the urgency of human factors which contribute to perhaps 75% of aircraft mishaps. Traditionally, when aircraft technology outstrips the ability of the human operator to function in the aerospace environment, the technology is scaled back to accommodate the human. The challenge for aerospace researchers today and in the future is to help the human operator keep up with, or even ahead of, the burgeoning technology.

Text: We will know more about future pilots than we know about pilots flying today. The *Neuropsychiatrically Enhanced Flight Screening* program (N-EFS, 1) specifically addresses the need for pilot selection beyond mere medical qualification. By the year 2020, N-EFS will have collected cognitive and personality-functioning information on in excess of 30,000 pilot candidates and will have follow-up occupational outcomes for the candidates who successfully complete Undergraduate Pilot Training. The objective of this flight screening program is to obtain longitudinal psychological testing data and then compare the results to actual performance when the trained pilot has been mission-tested.

A study of the psychological factors leading to success in aviation will enable researchers to select-in the most psychologically and cognitively suited person for the mission rather than only select-out those who are inappropriate. Previous efforts to predict aviator success on the basis of psychological testing have produced only minimally encouraging results (5). By the year 2020 we will be able to decide whether the N-EFS battery was able to successfully predict who went on to develop superior situational awareness (2), an ability certain to be at a premium in cockpits of the future. In addition, N-EFS captures baseline intelligence and cognitive functioning information on aviators, who are at high risk for traumatic brain injury, for idiographic assessment purposes. This baselining will allow head-injured pilots to return to the cockpit, or be cross-trained into nonaviation duties, sooner than is now possible as subsequent testing after an injury will be much more meaningful. It is more effective to compare individuals to themselves, rather than to norms derived from a pool of aviators.

Armstrong Laboratory Aviator Personality Survey: The *Armstrong Laboratory Aviator Personality Survey* (ALAPS, 6), currently in Beta test at the Armstrong Laboratory and the United States Air Force Academy, may be the world's premier psychological test for use with aviators by the year 2020. ALAPS is designed to assess the psychological characteristics of entry-level female and male pilots.

The development of the ALAPS was accomplished as follows: 15-18 dimensions of interest were identified, including both select-in and select-out domains. An initial pool of 24 items per scale was written. A sample of about 100 college students took an initial form to identify statistically poorly behaved items. Those items were replaced and the initial form was administered to 300 pilot candidates

through EFS. A final set of 16 items per scale was retained for the final form. Entire scales which failed to reach appropriate levels of reliability were eliminated.

By the year 2020, international norms will be well established, including profiles of individuals who complete extended tours on the International Space Station. ALAPS will aid selection of tomorrow's aviators, as it is an aviation-specific personality inventory. We plan to establish real-world, criterion, validity by correlating findings on the ALAPS to behavioral measures, such as simulator flights, peer evaluations, and flight performance reports on mission-tested aviators. Effective select-in measures established by N-EFS via ALAPS will be imperative with fewer cockpits, fewer aviators, and technologically sophisticated weapons systems.

Table 1. Scales of ALAPS

Validity

1. Reliability
2. Disclosure
3. Intra-individual consistency

Personality

1. Confidence/ Narcissism
2. Socialness
3. Aggressiveness
4. Order/ Compulsivity
5. Negativity/ Passive-aggression

Psychopathology

1. Affective Lability
2. Anxiety
3. Depression
4. Somatic Concern
5. Alcohol Abuse

Work Styles/ Crew Interaction

1. Dogmatism/ Authoritarianism
2. Deference/ Submissiveness
3. Team Oriented
4. Communication Openness
5. Organization
6. Impulsivity
7. Achievement/ Persistence
8. Risk Taking

Defense Women's Health Research Program: Appropriate training will be a pressing need for effective aviators and flying squadrons in the year 2020 and beyond. Two studies funded by the *Defense Women's Health Research Program* (DWHRP), accomplished by the authors and the Armstrong Laboratory, demonstrated the training need, especially in mixed-gender flying squadrons. *Assessment of Psychological Factors in Aviators* (APFA, 3) attempted to improve our understanding of the psychological make-up of mission-ready male and female pilots, using computerized psychological testing and face-to-face interviews. Psychological testing revealed more cognitive similarities than differences between male and female pilots. Not surprisingly, pilots' personalities were found to be low in neuroticism; pilots were extroverted and conscientious.

The interviews accomplished during APFA demonstrated many more differences between men and women that have implications for training in the increasingly mixed-gender flying squadron. The air forces of the future will surely include many more women and they will likely compete on an equal footing and may be represented in all cockpits. Men and women had different factors motivating them to fly. More women chose to enter pilot training because they went to the Air Force Academy and were pilot qualified, while more men chose to enter pilot training because they wanted to fly since childhood. Both combat and POW (prisoner-of-war) concerns were areas of significant differences of opinion, as well as, some agreement between men and women. The vast majority of both male and female pilots wanted to fly in combat or combat support roles, felt comfortable flying in combat with both genders, and most felt prepared to be POW's because of the training they had received. Concerns about the safety of women in combat and POW situations was, however, voiced by a majority of men, whereas women did not have the same concerns for another pilot's safety due to his or her gender. Many men believed it was a part of their personal code of ethics to be more protective of a woman in a dangerous situation. Many also believed women had a greater potential to be harmed in a POW situation than a man. More women voiced concerns regarding sexual assault and being used to exploit other POW's, while men were concerned about physical harm and their family's reactions back home if captured. These differing concerns call for improved resistance training in areas of sexual assault and gender relationships in war.

Again, both similarities and differences were seen between the experiences of men and women in the arena of stress and stress coping. Men more often believed women in their squadron had greater

stresses than themselves, whereas women felt the stresses of men and women were the same. Some women reported sexual discrimination as a significant career stress, while men did not have this concern. While both the majority of men and women reported either positive or neutral working relationships with both genders in their squadrons, older male enlisted crew and some commanders were reported to have the most difficulty dealing with the presence of women in their squadrons. The way men and women coped with their various stresses was very similar, however. Most reported coping with stress either through exercise or keeping their problems to themselves. These findings again point to training needs. "Old Guard" squadron members who are uncomfortable with mixed-gender squadrons can learn knew ways to interact with all of the members of their squadron and improved aircrew training in stress coping skills can be accomplished.

The currently ongoing DWHRP-funded study, *Psychological Factors of Aviators' Success*, (PFAS) marries the N-EFS program with the testing and interview methods established in *Assessment of Psychological Factors in Aviators*. PFAS will bear fruit and answer the question of whether female pilots are self-selected into aviation or if they are shaped as a result of the process of pilot training. The question is an important one, especially after finding that more Air Force women choose an aviation career as a result of attending the Air Force Academy than due to a life-long dream. This study will lend answers to both selection and training questions through its design of providing computerized psychological testing, to include the ALAPS, as well as a the *Aviator Occupational Interest and Concern Questionnaire*, a computerized survey similar to the interviews conducted on the mission ready pilots previously studied. In this way, the many pilot candidates can be compared to incumbent pilots and occupational outcome can be correlated with both testing and attitudes. By 2020 there will be a cadre of USAF female pilots who have completed an entire military flying career without facing *any* institutional limitations on which airframes they could fly. Such a population will be instructive for the other air forces of the world.

Increasing collaboration between nations' air forces can be addressed through methods similar to those used to study mixed-gender squadrons. Cultural differences and expectations regarding the roles of men and women must be considered in any future, multinational co-operative effort. Cultural differences may lend similar difficulties to the integration of aircrews as did the inclusion of women in all types of USAF flying environments. Crew coordination, squadron relationships, mission effectiveness, and flight safety are all affected by the gender and cultural make-up of the flying unit. The comment by a Russian general that "women love to clean" in response to the arrival of American female astronaut Shannon Lucid to the space station Mir (p. 23, 4) is an example of the challenges ahead.

The last challenge for the aviator of the future will be the ever-changing enemy. As nation-states and political systems rise and fall so to will the nature of warfare and war machines. The cognitive abilities and personality make-up of combatants may need to change with both the enemy and technology. Pilotless aircraft and advanced spacecraft lend unique challenges to the psyche of the operator, as does rapid change from localized flare-ups to global nuclear threats. Experts in psychological research will be tasked to help aviators and policy makers keep the operator up with the rapid changes. As we invest increasingly large amounts of money into each individual airframe and mission, we must learn more about the human in the equation, whether pilot or operator of an uninhabited aerial vehicle.

Discussion: Selection and training demand research attention to ensure the compatibility of future pilots and highly advanced technology. These areas are even more important when several other changes are considered, including: fewer pilots and aircraft to accomplish the mission, greater numbers of female aviators, increased collaboration between nations, and an ever-changing threat.

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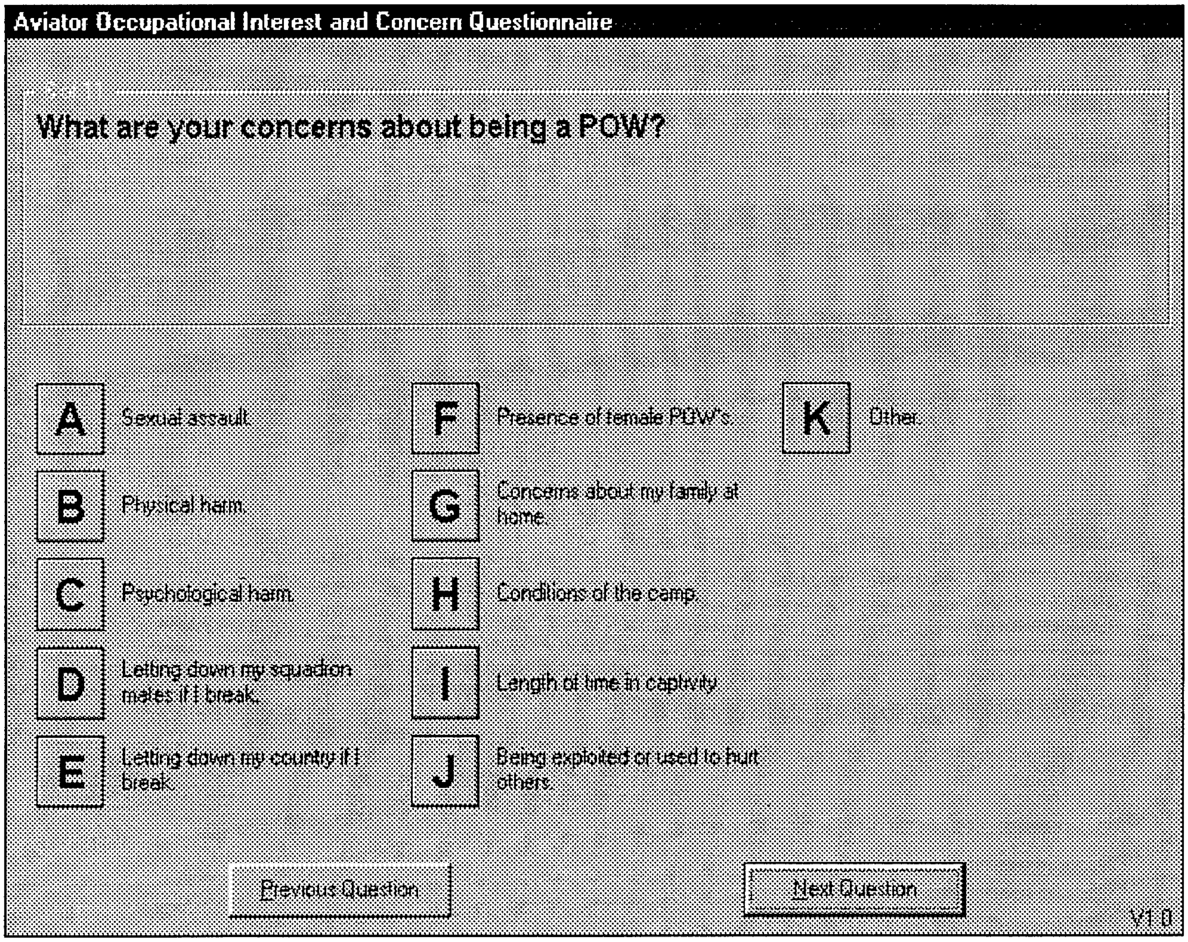


Figure 1. Computerized survey

Laser Generated 3-D Space Display Images

J. Taboada, Ph.D.

Abstract

Conventional techniques of forming three dimensional (3-D) images on a two dimensional screen involve the use of electronic or optical tricks, such as the use of special eyewear. In a 3-D space display, however, the images are formed directly from luminous points distributed in all three spatial dimensions. Instead of pixels, one has voxels (volume-pixels). There are a number of approaches currently under development for 3-D space displays, some holographic and others mechanical, but the goal is to achieve a 3-D space display with no moving parts and a full 360 degree view requiring no special eyewear. This goal is within reach through the use of new two-photon laser photoexcitation techniques where two laser beams of different wavelengths intersect in a special transparent media. Fluorescence is emitted at the intersection where the combinations of the excitations creates the emissions. By multiplexing the laser beams throughout the media, a solid display object can thus be synthesized. This presentation will review the state-of-the-art of 3-D space display technology and develop a prospectus for future applications in air traffic control and mission management.

Introduction

The human visual system, as well that of any binocular vision equipped organism, has evolved to function in a three dimensional spatial environment with exquisite ease. Distance, orientation and XYZ position of objects are readily and rapidly comprehended. The reason for this success in function may be attributed the high neural priority allocated to the processing of spatial cues.(1) Both psychological and physiological depth cues are applied by the visual system to conceptualize three-dimensional scenes. These cues are the following:

Psychological

1. Linear perspective (distant objects appear smaller)

2. Shading and shadowing (shadows and objects blur with distance)

3. Texture gradient (distant object have less detail)

4. Color (distant objects are darker)

5. Aerial perspective (distant objects appear cloudy)

6. Occlusion (near objects hide distant objects)

Physiological

1. Motion Parallax (image changes as the observer moves in X, Y, and Z planes)

2. Accommodation (change in focal length of the eye lens)

3. Convergence (inward alignment of the visual axis of the eyes)

4. Binocular disparity (difference between left and right eyes)

Two dimensional imagery has of course been very successful using most of the psychological cues, for example, photography, cinematography, video and the various planar arts. As a man-machine interface, however, the addition of a third dimension allows for far greater access to control variables. For example, with two dimensions, an operator can point (with a mouse) to some 500X500= 250,000 points on a screen, but with a third dimension this would go up to 125,000,000. Since the human neural system has already allocated a very high priority to 3-D processing, namely by vision stereopsis, the added dimension may actually help in reducing the information overload. A good practical example of this is in air traffic control. A three dimensional presentation would help in visualizing aircraft locations in the vicinity of busy airports.

Generally, a 3-D display improves task performance in at least eight factors which would tend to justify the investment in its development.(2) These factors are as follows:

- What vs. where - not only is an object localized in 3-D space (where), the binocular visual input also helps identify the object in the midst of clutter (what).
- Visual noise filtering - the observer can easily cross correlate the signal from the object as it is registered in both eyes and at the same time reject monocular noise.
- Greater effective image quality - by involving both eyes, a stereo enhancement of apparent image quality is possible because retinal disparity cues are less dependent on image quality.

- Wider field of view - A stereoscopic display can provide a wider field of view by partially overlapping the left-eye and right eye formats.
- Luster and surface sheen - difference in luminance and color in the two separate retinas produce this perceptual quality . This perception is impaired with one eye only.
- Slope perception - motion parallax for monocular vision is not sufficient to perceive terrain slope. Terrain slope is much more easily perceived with stereo vision.
- "Twin engine" reliability - with at least a stereoscopic view, there are two relatively redundant signals from the scene, and a mission can be continued when one channel fails.
- Focus/fixation control - By employing two separate eye channels, object size and distance realism is improved by allowing the visual system to control its ocular focal state and binocular state.

Most of these factors apply to 3-D stereoscopic displays where two images are each presented separately to each eye. A 3-D space display would also feature these factors as well as the increased realism of motion parallax. With motion parallax, the observer can move about the environment of the object to optimize its localization and recognition. In the next section, we will discuss the technology that is closest to making 3-D space-filling displays possible.

3-D Solid Display Technology

In order to stimulate all ten depth cues, one actually must have a solid object illuminated by some environment lighting. Each point on the object emits (by reflection or scatter or possibly luminescence) spherical outgoing waves that are mapped by the visual system into an object concept to which all the depth cues point. To generate a synthesis of such an object requires a means of generating the multiplicity of emitting points that the object possesses. This is a challenging task. The only display that has actually achieved this effectively is the hologram. In holographic displays a near coherent light source is diffracted to produce a synthesis of the multiplicity of original photon spherical waves generated by the object when holographically recorded. A hologram is a true three-dimensional display, but motion and dynamic updating of holograms remains exceedingly difficult in practice. It may be possible in the future to fabricate the high resolution spatial light modulators required for this function. The required technology is not yet available in the laboratory. Two technical approaches for 3-D space filling displays appear very practical at this point and are reviewed below.

Spinning helix

An elegantly simple, albeit mechanical system for 3-D space displays is a laser projected onto a rotating helix, a device invented by Prof. Rudiger Hartwig in the early 1980's.(3) The principle is shown in Figure 1. A glass cylinder (3) contains a scattering helical surface (1) which has a single period around an axis of rotation (2). The surface of the helix scatters light at a point (5) where a laser beam (4) intercepts the helix. It is clear from this geometry that any point in the XYZ coordinate space can be accessed by the laser beam as an intercept point on the helix by simply moving the laser beam and spinning the helix about the Z axis. To create a 3-D "object" the laser beam must be moved (at fusion rates) about the desired space and modulated (off and on) to intercept the spinning helix along the locus of points defining the "object." The system creates illuminated "voxels" i.e., points in a volume of space.

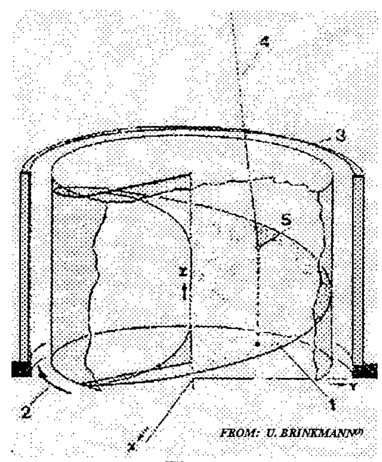


Fig. 1

The Research and Development Test and Evaluation Division (RDT&E) of the Naval Command, Control and Ocean Surveillance Center has developed a second generation version of this concept.(4) Using very rapid acousto-optic random access scanners, a large volume display with 40,000 addressable voxels at 20 frames/sec has been achieved. With the real-time presentation of underwater sonar data, the Naval group is considering application of the system for shallow water guidance of submarines and the monitoring of multiple torpedoes in three dimensions.

A demonstration of air traffic control has been performed by the Naval group. Using authentic data from the Identification Friend or Foe radar system at the Naval Research and Development in San Diego,

California, 80 planes in the San Diego airspace were displayed simultaneously showing flight information for any airplane in the 3-D volume of air space. Flight control could be accomplished from this presentation.

Multiphoton excited media

A step in the direction of a non-mechanical 3-D volume space display is the one achieved by exciting the points in a 3-D volume to generate visible emission. The principle for the display is borrowed from solid state laser physics. A recent development in solid state lasers has been the accomplishment of upconversion of infrared photons into visible photons in a specially prepared transparent media. Though the use of such a media (comprised of rare earth doped fluoride glass), and two infrared laser beams intersecting at a point, E.A. Downing and her colleagues[5,6] at Stanford University have demonstrated a 3-D solid state display.

Conceptually, the luminescent points in the solid are generated by a process known as two-step, two frequency (TSTF) upconversion. An energy diagram and schematic illustration of the process from E. A. Downing et.al. is shown in Fig. 2.[6] The conversion process starts with the absorbing ion in the ground state E_0 (Fig 2A) which is excited by a first IR photon λ_1 to level E_1 and subsequently raised to the highest level E_1 by a second IR photon λ_2. From the high state E_2, spontaneous decay to the ground state occurs only at the intersection of the two scanned beams as shown in Fig. 2B.

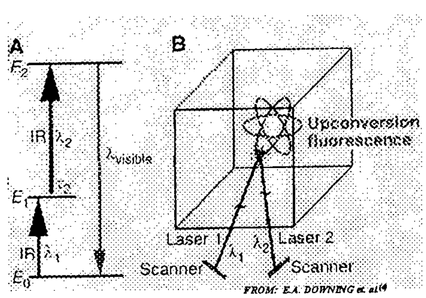


Fig. 2

In an actual prototype system, the media was Pr(3+ion) doped ZBLAN glass which has an efficient 2-step process for up conversion. A voxel is generated at the intersection of a laser beam at 1064 nm wavelength and a second beam at 840 nm. The apparatus is diagrammed in Fig. 3. In this system, a titanium sapphire (TIS) laser emitting at 840 nm is focused into a plane sheet in the conversion media. A second IR laser, a Nd-YAG source at 1064 nm is deflected into a circular path in the media by a rotating mirror. The intersection of the two beams is a circle in the media and, by the emitted upconversion light, it is visible in room light.

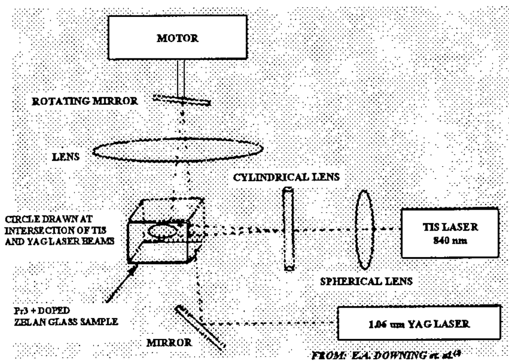
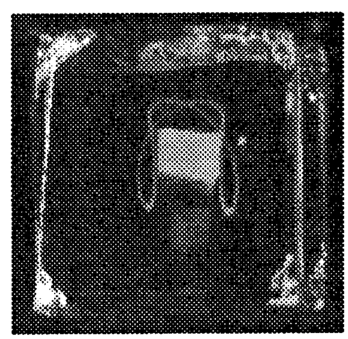


Fig. 3

By using a mixture of Pr^{3+}, Er^{3+} and Tm^{3+} lanthanide ions in the media, E. Downing et.al, have actually produced 3-D color "objects" visible in room light as shown in Fig 4.[6]


FROM: E.A. DOWNING et. al.[6]
Fig. 4

The energy level diagram for the system is shown in Fig. 5. The current status of this system is that it can display up to 30K voxels at about 60 Hz refresh rate. Although not as of yet applied to air traffic control, the display has the potential of accomplishing this function with more dynamic range because of the smaller moving parts. Also, if 2-dimensional arrays of lasers can be produced with the correct wavelengths, then the volume display can be achieved with no moving parts. This will be the ultimate "synthetic reality display."

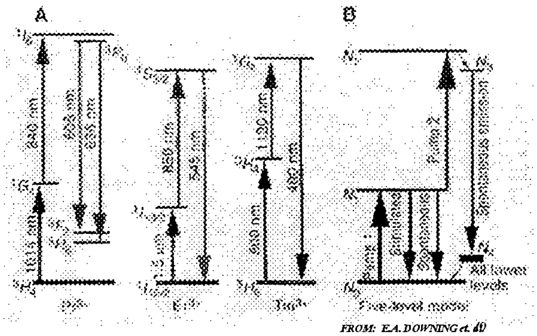


Fig. 5

Conclusions And Future Prospects

The importance of 3-D perception has been demonstrated by the high level of neural processing allocated to working with objects in 3-D space. Until a man-machine interface makes full use of this 3-D capability, there is limited operator control performance with flat panel displays. Two display strategies have been developed to start to address dynamic, 3-D, space filling displays. At present, air traffic control has been demonstrated with real data streams using a spinning helical device. Future developments may see the introduction of a system having no moving parts, generating 3-D "objects" in full color at dynamic refresh rates. Interacting with such "objects" will be as natural and efficient as working with the real thing.

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Pilot Testing in Virtual Environments

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In the 1980's, applicants to undergraduate pilot training were tested on verbal and quantitative achievement while seated at a desk with pencil and paper. In this decade, applicants are also tested on information processing performance and psychomotor performance while seated at a personal computer with joy sticks and a keypad. By 2020, applicants to undergraduate pilot training, could don goggles and data gloves and enter a virtual environment for the measurement of leadership and team work. Major improvements in pilot testing have been achieved by augmenting the measurement of verbal and quantitative achievement with the measurement of information processing and psychomotor performance. A large evidentiary basis has been established to demonstrate that pencil and paper selection tests measure the abilities important for piloting an aircraft. The addition of measures of information processing and psychomotor performance increment the validity of pencil and paper testing by more than fifty percent. The next major improvement in pilot testing could be accomplished by the measurement of leadership and team work by using virtual reality computer technology.

Estimates of leadership potential play an extremely important role in the pilot selection process. Currently, studies are underway to investigate the actual policies used by members of pilot selection boards in the process of identifying candidates for undergraduate pilot training. Applicants to pilot training come from several different sources. Applicants are provided through the Officer Training School (OTS), the Active Air Force, the Air National Guard (ANG), the Air Force Reserves (AFRES), the Reserve Officer Training Corps (ROTC) and the USAF Academy. Recently about half of the applicants have been provided by the USAF Academy and the other half have been provided by ROTC. For ROTC, OTS, the ANG and AFRES, applicants to pilot training are first selected for officer commissioning with reference to physical, education and ability minimums. After selection for officer commissioning, individuals who satisfy a second, higher ability minimum requirement, are permitted to apply for pilot training and are considered by selection boards. Board members are directed to base pilot selection decisions on leadership potential, educational achievement, physical fitness and ability based on both pencil-and-paper testing and computer-based ability testing. The USAF Academy uses a different procedure for pilot selection. Cadets who apply for pilot training must first pass a physical examination and job sample testing in the form of flight screening before they are considered by a selection board. Flight screening consists of 25 hours of instruction in a single-engine, propeller driven, low-wing aircraft. Board members are directed to base pilot selection decisions on leadership potential, flight screening performance, educational achievement and physical fitness. Leadership potential is one of the most important considerations in selecting pilot training candidates regardless of source. Yet, each individual board member must evaluate hundreds of applicants in a couple of days without the aid of a standardized measure of individual leadership potential. As a result, assessments of leadership are indirect, subjective and based on intuitive judgment. The extent of error in these assessments is unknown.

Computer technology could provide a controlled environment in which objective measures of an individual's performance as a leader and direct assessments of their team work skills could be obtained for use in pilot selection. The use of computers for creating team tasks has been demonstrated (Streufert, 1988; Morgan & Salas, 1988). Currently, research is underway in several United States universities and government laboratories to investigate team processes with the goal of developing training techniques for improving team performance. Lessons learned in team research could serve as the foundation for development of computer-based measurement of individual differences in leadership. The goal would be to develop a computer-based personnel testing system which could derive standardized, objective measures of an individual's leadership potential in the period of two to four hours. The time constraint imposed by decentralized personnel testing requires that the task environment be immediately familiar rather than technical. The resulting personnel testing system would be portable and deployable at several different test sites as opposed to being stationary and for use only in a personnel assessment center scenario. Furthermore, the ideal system would require no more technical support than a video arcade game. To attain this goal, the first stage would consist of conducting research to demonstrate that valid measures of leadership potential could be obtained in a simulated

environment using personal computers. If validity is established, the second stage of the effort would consist of transporting the task environment and performance assessment software to a virtual reality computer environment. Synthetic team mates, manifested as text or audio messages in the personal computer-based system, would be enhanced with realistic form and appearance in the virtual reality computer system.

In this context, a team would be defined as two or more synthetic team mates with the examinee in the position of leader. Standard scenarios would be developed to present decision making problems which have solutions based on a rational choice model. The decision environment would consist of information processing tasks and could lead to decisions which have varying risk to gain ratios. Some decisions would have low risk with high gain; others would have high risk with low gain. Team interaction would consist of the examinee querying synthetic team mates for information and directing them to obtain specified scenario status information. The focus would be on the acquisition and sharing of information and decision choices made by the examinee. After being provided with scenario status information from the system and from synthetic team mates, the examinee would be repeatedly confronted with a series of choices among discrete alternatives leading to a well defined goal. Measurement would be directed to an examinee's performance as leader while interacting with synthetic team mates. The examinee would be queried to assess the accuracy of his or her view of the task environment, to assess the accuracy of information processing, frequency of information sharing and accuracy of decisions. The scoring of more and less effective decision choices would be based on input from expert and novice managers. Interpersonal functioning could be assessed by measurement of communication effectiveness under varying constraints. Interpersonal constraints on performance could consist of differences in team member rank, gender, ethnicity, personality and ability. Additional performance constraints could be introduced in the form of increasing the task load, task complexity and ambiguity of information. A concurrent approach to validation could be adopted. The validity of leadership scores could be examined for managers who supervise different numbers of personnel, managers who are at different rank levels and groups of mangers judged as successful and unsuccessful. Transportation of the team task environment and performance measurement software to virtual reality computer environment would be contingent upon the demonstration of validity. The development of a valid leadership assessment technology for pilot testing, could provide standardized objective measures of individual differences in leadership which would improve current assessments based on intuition and subjective judgment.

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Fluid Dynamics Panel

Contents

1. Introduction

This chapter is intended to highlight prospects and challenges of some topics of Fluid Dynamics considered to be critical to technology advances which are discussed in Volumes I and II or in other chapters of Volume III. Therefore it is not an exhaustive discussion of all of the required research in Fluid Dynamics necessary for technical leadership in the 21st Century. In this regard, the reader may not agree with the inclusion of some topics and the ommission of others. The content reflects the concensus reached within the AGARD Fluid Dynamics Panel on "critical" topics.

This chapter was written by the Technical Committees of the Fluid Dynamics Panel which are:

- Computational Fluid Dynamics (CFD)
- Wind Tunnels & Testing Techniques (TES)
- Fundamental & Applied Aerodynamics (FAA)

It is hoped that the reader will find the material not only enlightening but also it will serve as a basis for stimulating discussion on future research.

2. (CFD) Computer Dependent Developments, Prospects and Challenges

2.1 Introduction

Computational fluid dynamics (CFD) has perhaps been the most influential tool in fluid mechanics in the last quarter century, mainly because it existed only embryonically twenty five years ago, and because new tools always give rise to new developments. Much of what has happened in these years has been in the field of scientific research, and has only partially filtered into engineering design. It is to be expected that this transfer will be the subject of next decades and that, twenty five years from now, CFD will be as indispensable a part of development and design as it is now in the field of science. Several actions will have to be taken for this to happen, some of them dealing with fundamental issues, but many in the form of integration and implementation efforts for techniques that exist now or which are in the late stages of research. This will require a sustained effort and some large scale coordinated projects, especially in such complex areas as flow physics and efficient numerical methods applicable to arbitrary complex geometries, but the rewards are substantial. Even if the naive idea of the demise of conventional wind tunnels is unlikely to be realized in the foreseeable future, the routine integration of CFD in industrial design promises vastly reduced development cycles for aircraft, and the possibility of identifying optimal solutions which can, at the moment, only be obtained by trial and error or in many cases not at all. Another exciting possibility is the real-time use of approximate CFD techniques in the optimization of aircraft configuration during flight, including its integration with smart structures, which may result in substantial increases in range and operational capabilities. Finally, an obvious use of CFD is the design of vehicles for which physical testing (ground or flight) is impossible or difficult, such as highly hypersonic vehicles, for which computational testing, even if incomplete, might be the only available option.

Many of the problems in CFD are associated with the presence of widely separated relevant length scales, which is a consequence of the basic physics of turbulent flow. Three basic computational strategies are used. In the Reynolds Averaged Navier Stokes approach (RANS) all scales smaller than those defined by the vehicle geometry are modelled. This is the fastest and least accurate route, and almost the only one currently used in industrial applications. The opposite strategy is Direct Numerical Simulation (DNS) in which all flow scales are computed, and which is therefore virtually error free, but whose computational cost is so large as to make it of little practical industrial importance. It is mainly used in basic research, and it is likely to remain that way in the foreseeable future. Large Eddy Simulation (LES) is intermediate between the two, in that only the largest scales are resolved while the rest are modelled. It is a compromise in cost and accuracy, and represents the most likely strategy for the development of industrial CFD in the next few decades.

An exception to the assessment in the previous paragraph might be the design of the small vehicles likely to arise in the next decades from the drive towards miniaturization and unmanned operations. While it will surely be impossible to DNS a full configuration for a present fighter or transport, a low speed drone in the 1-2m size range might be within the future capabilities of DNS.

The following sections expand on these themes for those fields of aerospace technology in which CFD is expected to have the most impact in the next quarter-century, or for which a more concentrated effort is seen as necessary. Hardware development is reviewed first. Computers are the tools of CFD and they still pace its progress. Numerical and computational issues are treated next, including grid generation and the interactions with control theory, followed by an appraisal of which are the problems and prospects in the field of flow physics. Lastly, the final sections deal with two particular classes of vehicles which pose computational problems substantially different from the rest: hypersonic craft and helicopters.

2.2 Computing Power Outlook

Computer speed has grown in the last decade by an order of magnitude every five years, although a longer historical perspective suggests a somewhat slower rate of growth. The largest computer centers today provide power in the order of a Teraflops, usually in the form of several hundred connected CPUs. "Commercial" (M$30) computers of that capacity are expected by the year 2000, and the extrapolation to 2020 is for commercial computers in the range of Petaflops (10^15). This would allow the direct numerical simulation of local patches of turbulent boundary layers with momentum thickness Reynolds numbers of the order of 50,000, equivalent to a few square centimeters of wing, located two meters downstream from the leading edge of a commercial transport. While it is difficult to exaggerate the theoretical importance of this capability, which is in the asymptotic Reynolds number range of the flow, it is still orders of magnitudes away from immediate industrial applications.

It is nevertheless argued below that we should be able by that time to undertake large eddy simulations of full configurations in a few seconds, based on the theoretical advances derived from this "research" computer power. From the hardware point of view, the requirements are processing speed, storage capacity, pre-processing capability, graphic post-interchange, and communication bandwidth for the exchange of data and for the use of remote facilities. We have already discussed the outlook for computing speed. Central memory has historically kept pace with it, the rule being about one byte per flops. Mass storage and the associated search and data base software have grown slower, and there is a danger that they will be outstripped by the other components. At least a hundred times more secondary storage than central memory will be needed, or 10^17 Mbytes for a typical installation. Semi-archival storage should be at least 1000 times larger. The way in which this computing power is expected to be implemented is through massive parallelism, requiring an intensive effort in software engineering for its routine utilization.

2.3 Pre and Post-processing

The numerical solution of any problem in fluid dynamics requires the construction of a grid to define the points at which the approximate solution is computed or the elementary volumes used in the discretization of the equations. This preliminary work to the actual running the code is still a pacing item in CFD. Generation of grids around complex arbitrary configurations IS now possible, but it IS NOT industrially viable. It may require days or months of elapsed time and may consume 80% of the total man-hours. Even though tools have gained great sophistication, they remain cumbersome and restrictive, and require skills that are not generally available in designers. An important challenge for the next quarter century is to reduce the time needed for this task and thus the cost of CFD analysis. There are two critical bottlenecks: surface modeling and handling of the geometries, generation of optimum grids for a given geometry and physics.

The first issue relies at present on the use of CAD systems that were developed before the current advances in grid generation technology. Those tools must now be redesigned to accommodate computational analysis as well as tooling and material formation. In parallel to this task several features must be improved, such as CAD system independence, the efficiency and accuracy of the interfaces between different CAD systems without loss or modification of the geometric information, the treatment of often imperfect CAD data with gaps, overlaps and tolerances, and the handling of scales differing by several orders of magnitude for high Reynolds number flows.

On the second issue, recent years have witnessed the development of a multitude of structured and unstructured gridding strategies: multiblock, embedding, overlapping, chimera, quadtree-ctree, etc. Each of them has known advantages and drawbacks, and the difficulties lie in the choice among them, in the determination of grid topology (the relative arrangement of the different parts of the grid), and in the handling of hybrid meshes combining several strategies; the latter is also an important problem in the development of flow solvers. Cost reduction will also be achieved by ensuring that the grids passed to the solvers are appropriate and cost effective. This will require improvements in the criteria to characterize grid quality, or to define the optimum location of the points to minimize errors and capture flow features, in the development of techniques to build grids satisfying those criteria, and in control procedures to check grid performance and to suggest improvements when needed.

The cost of the overall grid generation process will also be reduced by improving the ways in which the designers interact with software. In recent years a tremendous effort has been put into improving interactively, which has resulted in a large increase in the complexity of the shapes that can be treated. However, while these interactive tools are well adapted to the generation of grids about unique configurations, their generality relies to a large extent on human interaction, and they are of little or no use to designers who need to repeatedly mesh and solve a series of similar gementry's; for example, even for small changes like those resulting from MDO (multi-dimensional optimization) cycles, a lot of manual input is needed to redefine the grid. In contrast command-line interfaces allow repetitive tasks to be easily automated and repeated with little

or no user interaction, and grids generated or modified in a batch environment, and controlled via a user script allow the code to be incorporated into an MDO loop. The development of grid generation tools combining all possible interaction models (batch, graphically interactive, automatic, programmed, parameterized, macro-commanded) must be emphasized. Examples of such coupling between modes are scripting of batch tools for fast parametric variations within new classes of geometrys, creation and use of grid generation libraries associated to families of topologies, creation of an easily understandable non-graphical editable batch counterpart whenever interactive tools are invoked.

The tools of artificial intelligence and expert systems should be used to achieve this automation and to help in simplifying such presently complex problems such as sub-structuring and domain decomposition, based possibly on previous experience, problem geometry and flow analysis. If full automation is not possible a code should be able to suggest alternatives for corrective actions, to check user input for range and reasonableness, and to do its best to help the user.

Grid generation has now reached a stage where a multitude of techniques are mastered and ready to use. The difficulties lie in combining and coupling them optimally in a given situation; the way this is done will considerably influence the use of CFD in the future.

With the appearance of computers with ever larger memories, and with the development of CFD codes able to handle very refined meshes and complex unsteady problems, the designer is presented with huge amounts of data to analyze; this tendency will continue in the future. Post-processing tools must help him or her to study the flow locally and globally to obtain the relevant values, to eventually understand what went wrong in a computation, or to decide how to modify the solution procedure. Development of new post-processors should concentrate on improving productivity by using sophisticated memory management techniques to increase system throughput while reducing memory requirement. Software able to distribute post-processing workload should be designed in order to facilitate the handling of extremely large data sets to efficiently use networked resources. Attention should also be paid to new features dedicated to transient analysis, including animation and video recording.

Graphic power for the preprocessing of geometry and for the post-processing of results is perhaps the weakest link in the simulation chain. What is needed is the capacity to interactively manipulate whole flow fields in three dimensions and time, both graphically and quantitatively. In twenty-five years this will imply arbitrary grids and geometrys, involving time series of one thousand fields, each of them containing 100 million grid points. Although there is no way to predict how this will be achieved, it is in line with past historical evolution. Other industries, particularly in the entertainment area, share the need for storage and graphic capacity and are likely to provide the commercial pull, but care should be taken that the particular needs of aerospace are considered, especially quantitative diagnostics and volume rather than surface data.

2.4 Multi-dimensional Optimization

During the last two decades major advances have been achieved both in control theory and in our capability to calculate complex aerodynamic flows. In control theory there have been far-reaching developments in the design of robust controls for systems with incomplete or noisy information, and uncertain or varying plant parameters. Concurrently methods have been developed to treat distributed parameter systems, governed by partial differential equations. In fluid mechanics the focus has been on the development of computational methods to calculate complex flows. Mathematical models of fluid flow are available at widely varying levels of complexity, ranging from Laplace's equation for ideal (incompressible inviscid) flow, the subject of classical theories of hydrodynamics, to the Navier-Stokes equations for incompressible and compressible viscous flows, and the Boltzman equations for rarefied gas flows.

In parallel with these advances in control theory and aerodynamics, rapid advances in computer technology have made it feasible to tackle increasingly complex problems. In the light of these developments, there now appears to be the potential to realize significant benefits by merging control theory and fluid mechanics in several important problem areas. These can be distinguished broadly as vehicle control, flow control, and aerodynamic design problems. These categories are not strictly exclusive and some problems can properly be regarded as belonging to more than one of them.

Within the first class, the shape design of an aircraft or a ship and the design of its control system are strongly interdependent. Also within the first class of problems, there are important opportunities to reduce structural weight by the use of the control system for gust alleviation and flutter suppression, as well as trajectory control during maneuvering.

Within the second broad class of flow control problems there immediately comes to mind the possibility of both active and passive boundary layer control to prevent or delay transition to turbulence. The feasibility of delaying transition by distributed suction is well known. This is an example of active control, but without feedback. It can, however, be

effective, and it is largely the manufacturing and operational problems such as production cost, surface accuracy, and maintenance of surface quality that have prevented its introduction and use. Issues arising in the development of a feedback control to prevent transition include the effectiveness of possible boundary controls (temperature, or compliant surface), the question of what to measure and how, and the speed required for on-line computation. Passive control might also be effected, for example, by using the pressure difference created by the flow to generate a bleed through a porous surface on the underside of the wing. The shape may also be designed to delay transition: this belongs to the third category of design problems.

Another opportunity for flow control is found in compressors for jet engines. Compressor performance is generally limited by blade stall leading to surge, beginning with the appearance of a rotating patch of stalled flow. It has been demonstrated that the onset of rotating stall can be delayed by active control of the blade pitch angle.

The third class comprises a wide range of shape design problems. Any aerodynamic device, such as an airplane, a wing or a ducted fan, may be regarded as a way of controlling the flow to realize some desired objective such as lift or thrust. Consequently the design of these devices may be considered as belonging to control theory (in particular to the control of partial differential equations through boundary conditions), where the form of the control is the variation of the actual shape of the boundary rather than some input such as pressure. The shape might be varied during the operation of the system, as is the case with movable flaps or control surfaces on a wing, but such variations are generally feasible with only a few degrees of freedom, such as extension and angular movement of a flap. The basic shape, treated as infinitely variable, has to be fixed during the implementation of the design. This is essentially a form of off-line control which can be calculated once and for all, making it possible to tackle fairly complex non-linear problems which might otherwise be computationally infeasible.

This offers a route to bring CFD methods directly into the design process to find optimal aerodynamic shapes for a given set of objectives, whereas present CFD methods have been largely limited to the analysis of flows over given shapes. If the analysis indicates that a given shape fails to meet the objectives, it has been up to the designer to use his intuition and experience to devise another one. Such a process of trial and error is typically both lengthy and difficult, with no assurance of the optimality of the final design. Formulation of the design problem in the framework of control theory reduces the design process to a systematic procedure which can be implemented on a computer. Preliminary studies have demonstrated the promise of this approach. In particular, it has been demonstrated that three dimensional wings can be automatically redesigned to improve their transonic performance by reducing or eliminating shock waves which would otherwise appear in the flow.

It has also been demonstrated that a wing can be optimized for best average performance over several design points at different flight conditions. The method has been used to design hydrofoil sections which achieve higher speeds before the onset of cavitation by limiting the peak suction over a range of lift coefficients. Building on these initial successes there is a unique opportunity to press on the development of such powerful methodology and its application to the design of more complex devices such as rotating machineries. There are also opportunities for extension of this methodology to fields other that fluid dynamics (i.e. manufacturing). These extensions will require continued advances in algorithms for solving problems governed by PDE's on parallel computers, as well as the continuing development of optimization techniques.

2.5 Flow Physics: Turbulence Modelling

Turbulence is now one of the limiting factors in CFD computations of complex flows. The inability to model it properly prevents designers from computing and optimizing drag and separation, and therefore the range and agility of aircraft, as well as from minimizing noise, wake generation and acoustic fatigue, and from controlling such undesired side effects as vortex breakdown and some types of gross flow instabilities. On the desirable side, for example, drones without moving control surfaces have been demonstrated by exploiting the detailed behavior of local turbulent flows, but such applications can, at the moment, only be developed and tested by trial and error and tunnel testing.

A summary of the current turbulence modelling status can be found in the Fundamental Aerodynamics chapter of this volume (ref: sec. 4.2). For the low-order velocity moments which are relevant to technological applications, turbulent flows are universal as long as their vorticity fluctuations are larger than the externally imposed strain, and faster than the time scale dictated by the unsteadiness of the boundary conditions. For large enough Reynolds numbers, this is always the case for the smaller eddies in the flow. Reasonable models exist today for small scale turbulence away from walls, and large-eddy simulation (LES) has been introduced to take into account the large scales which are unsteady and dependent on the details of the imposed boundary conditions. While these methods are only now beginning to be validated, and although fundamental work is left before they

are understood well enough to be trusted in general situations, it is clear that they should be able in the next decades to reproduce most free turbulent flows at low to moderate Mach numbers. Since they only have to simulate directly those eddies which are comparable to the scales defined by the gross flow distortions, their resolution requirements are potentially comparable to those of Renolds Averaged Navier Stokes (RANS), i.e. a fixed number of points across the boundary layer. Their inherent unsteadiness requires that they be run for a sufficient number of time steps to achieve steady statistics, but this is comparable to the number of iterations needed for convergence in steady RANS computations.

The main roadblock in the way of the practical application of LES is the simulation of near wall turbulence. Most practical problems include walls and, in particular, the principal contribution of turbulence computations to the simulation of aircraft configurations is in the behavior of the boundary layer. Near a wall the shear is always of the same order as the turbulent vorticity and LES, as defined above, has to reproduce all the turbulent scales. This makes its resolution requirements comparable to those of direct simulation, and much beyond the capacity of any foreseeable development in computer hardware. The physics of wall turbulence are, however, also qualitatively understood, and can probably be reduced to a few universal cases, each of which can be modelled separately. The limiting scales are those introduced by pressure gradients parallel to the wall and are also of the order of a fraction of the boundary layer thickness. The problem of modelling the wall region is one of active research at present, and a conservative estimate is that, if the present rate of progress is maintained, models will be available within the next 10-15 years. Taking into account the need for validating and incorporating them in existing codes, they should be operational within the time frame of this study. At that point, the resolution requirements for the reliable LES of aeronautical configurations would be comparable to that needed today for RANS. This would include such "difficult" problems as the prediction of separation from smooth surfaces, complex geometrys, unsteady maneuvers, and aerodynamic interference. Problems that will probably still be outstanding in the year 2020 are highly compressible turbulence, where the fluctuating Mach number is substantial, and flows involving chemistry, dissociation and combustion, for which an adequate physical understanding is missing at the moment. A closely connected problem, the prediction of transition, is treated below.

The previous discussion does not imply that full aircraft configurations will be easily computed in 25 years. Under the assumptions explained above, the requirements for the LES of an aerodynamic configuration with a chord Reynolds number of ten million are about ten million grid points and ten thousand time steps. Assuming 100 operations per step and grid point, a Teraflops machine would process it in about 10 s. But this assumes, besides the turbulence modelling advances discussed in previous paragraphs, advances in: clean, locally adaptive numerics, automatic grid regeneration, and the ability to dynamically run different physical approximations on different parts of the flow. Nevertheless, the outlook is (assuming that aggressive research in this area is not abandoned), turbulence modelling will probably no longer be a pacing item for engineering aerodynamic simulations twenty five years from now, but rather, as shock waves are today, one more factor to be integrated in increasingly complicated numerical codes.

2.6 Flow Physics: Transition

Laminar-turbulent transition is highly initial-condition and operating-condition dependent. The availability of careful, archival experiments for comparison is the main issue for the validation of theoretical and computational predictions and models; few exist. The CFD formulations validated to date demonstrate that if the environment and operating conditions can be modelled and input correctly, the computations (nonlinear Parabolized Stability Equations and DNS) agree quantitatively with the experiments.

Ongoing efforts in spatial computations have been vigorous and have recently realized successes in the improvement of numerical methods to reduce the required computer resources, in the prediction of more complicated physical processes, and in the explanation of the different mechanisms at work in the experiments. The downstream boundary condition also seems to be more under control now.

Spatial DNS are still too expensive for use in routine design [O(1000) CPU hours on a CRAY] and at present we cannot provide a completely resolved solution all the way through transition to turbulence even on a flat plate. However, an important and exciting role for the simulation is in the development and calibration of simpler models. The abundance of information provided is invaluable and complements any experimental effort.

Challenges for simulations include:

- Solutions for complex 3-D geometries including the complete transition to turbulent flow, bypasses including 3-D distributed roughness, and better understanding and specification of the free-stream environment.

- Successful CFD simulations of available complete experimental databases

- CFD leadership in the determination of relevant effects in validation experiments for supersonic and hypersonic flows (including chemical reactions)

- Simulations for the high Reynolds numbers and operating conditions of flight.

- Use of parallel machines and algorithms developed for more efficient and accurate solutions.

2.7 Computational Methods for High Speed Flows

Monte Carlo methods have a long history of application to the problems of hypersonic flow about vehicles operating in the near vacuum conditions of the extreme upper atmosphere. In these rarefied flows the continuum approximation breaks down and the flow field must be analyzed from a kinetic theory point of view based on the Boltzman equation. In the Direct Simulation Monte Carlo (DSMC) approach, the trajectories of a collection of individual gas molecules are followed in position and momentum space. As the motion of the gas ensemble progresses forward in time, collisions between molecules are computed using elementary rules which conserve momentum and energy. With the advent of supercomputers, and especially parallel processor machines, significant progress has been made in this field in the last ten years. The number of molecules in the ensemble has increased by roughly three orders of magnitude from simulations containing roughly 50,000 particles in the early 1980's to recent simulations which exceed 100 million particles. Moreover the technique can now be applied to flows over complex shapes.

However most problems of practical interest have regions where the density is high enough to warrant the use of a continuum approximation. This is especially true of bodies which high cooling heat transfer rates at the surface. Therefore the challenge now is to develop accurate hybrid schemes which combine the DSMC method with a Navier-Stokes representation. Progress in this development requires compatible kinetic flux-vector splitting for the Navier-Stokes part of the scheme. This has recently been achieved, and the required fluxes have been obtained from the Chapman-Enskog velocity distribution function, permitting realistic simulation of nonequilibrium effects which include first-order velocity and temperature slip conditions at a solid surface. With the advances in computer speed and memory which are expected over the next two decades there is every reason to expect that the DSMC method will mature into a standard design tool for hypersonic vehicles operating over a wide range of altitudes.

2.8 Helicopters

Helicopters present several problems which are specific to them in the context of CFD. One of them is the aerodynamics and aero-acoustics of the rotor in forward flight, where each blade experiences both transonic flow at low angles of attack and low speed flow at high angles of attack during a single rotation. The dynamic behavior of airfoils in transonic flow is still an unsolved problem both experimentally and numerically. Even more challenging is the low speed case, and especially the prediction of dynamic stall, where pronounced hystersis effects are still not understood. Another important problem is blade-vortex interaction which induces vibration and generates noise. The problem of simulating full configurations is common to other types of aircraft, but it is compounded here by the abundance of moving parts and by the necessity of rotating independently parts of the grid to model the interference of the rotor with the fuselage, with the tail plane, and with the tail rotor, as well as by the need to predict and minimize the unsteady loads generated by those interferences. Closely related to the aerodynamics problems are those of aero-acoustics, in which high-speed impulsive noise, blade-vortex interaction noise and broad-band noise have to be computed and analyzed.

Very specific problems arise from the new configurations such as compound helicopters or tilt-rotor aircraft, in which the interaction between rotor and wing is especially tight, and in which the optimization of the rotor for very different operating conditions requires high-quality prediction and design methods.

Experimental investigations of airfoils and blades in wind tunnels and flight are required, and CFD methods to model the various effects have to be developed. Specially important are advances in grid generation, advanced numerical schemes with proper conservation properties across moving grids and turbulence modelling. A particular requirement of vortex interference prediction is for schemes that correctly conserve trailing vortices away from the blade surface.

The solution of these problems is essential if helicopters are to continue improving their performance, operational capability and environmental friendliness.

3. Prospects and Challenges in Wind Tunnel Testing

3.1 Introduction

3.1.1 Present Situation

The process by which a complete aircraft design is arrived at today, is a largely serial sequence of design processes within individual disciplines. The aerodynamicist takes most of a year or two to define the external lines, followed by loads determination and then structural design with systems people struggling to find space for their systems; last in line are the fabrication people who have to build the design, and the cost ends up being whatever is necessary.

Within the Aerodynamic Design Process, the roles of wind tunnels and CFD have evolved, to date, in ways that are complementary and which properly exploit their current respective strengths in terms of relative costs and flow time. Their optimal usage is concentrated at opposite corners of the spectrum. The strength of CFD is the ability to carry out, rapidly and affordably, a very small number of simulations. The strategy that has evolved for exploiting this strength is to concentrate CFD design on those areas of the flight envelope which include cruise, take-off and landing. These are the regions that most influence the operational efficiencies of the aeroplane: but the aeroplane handling characteristics, its ability to recover from upset conditions, and its performance must be accurately known throughout all regions of the flight envelope. That entails literally hundreds of thousands of simulations, with each combination of Mach number, angle of attack, angle of yaw, aeroelastic deflection, and control surface positioning constituting a separate simulation. The strength of the wind tunnel is to be able to carry out those hundreds of thousands of simulations within acceptable limits of costs and flow time, a task that is currently unthinkable with CFD.

From this description, it might be imagined that this is a stable situation, and that the current roles will persist well into the future; within Aerospace 2020 it is important to challenge such assumptions. In examining the specific role of a certain tool - CFD or wind tunnel - in a design process, it becomes apparent that each occupies a rather well-defined "range of usefulness" within the timespan of the overall design process. The upstream end of the range is generally established by cost and flow time. At this upstream end of its range the code or wind tunnel is competing with other tools that are faster and cheaper to use. The downstream end of the range is generally restricted by limitations on variation (i.e., reliability and accuracy). The downstream portions of processes are increasingly demanding of low variation, and tools whose variation is higher cannot have a role in the downstream portion of the design process. Thus the exact balance, at any particular time, between the use of wind tunnels and CFD will depend on their relative accuracy of prediction at the downstream end, and the rapidity with which they can supply answers at the upstream end.

The challenge to wind tunnel testing, or even wider to Experimental Fluid Dynamics (EFD) in total, is:

- to maintain, or enhance, the reliability and accuracy of the data it produces in comparison with CFD and Flight Testing
- to decrease the time taken for it to be able to supply results into any given programme.

3.1.2 Future Situation

One serious consequence of today's ponderously slow aerodynamic design cycle has been to limit our ability to make the proper cross-functional trades involving aerodynamics, loads, structures, systems and manufacturing. The time and resources needed by the aerodynamicist to arrive at a final aerodynamic loft has become so great that the ability to trade aerodynamic shape and performance for advantages in the other disciplines in rapid fashion during the design process has been quite restricted. But it is likely that all of that will change in the future. Already we are seeing radar signature considerations having a comparable influence to that of aerodynamics on the exterior shape of the aircraft. The ultimate challenge is to be able to carry out the detailed design of any portion of an aeroplane within weeks at most, and to do it in concert with the load engineer, the structural designer, the systems person, and the manufacturing expert sitting side by side in the same room, with computer systems that talk well with one another. From the aerodynamist's viewpoint this requires the following tools that are always available to supply answers to specific aerodynamic questions; fast computers immediately accessible with rapid CFD methods; wind tunnels that are waiting for rapid, but short entries; and ability to design and build models rapidly.

In order to allow wind tunnel testing to continue to play a significant part in this new design process, an entirely new paradigm will have to be developed for the design and fabrication of wind tunnel models, the operation of existing wind tunnels, and the management of these processes. Model definitions will have to move rapidly from the aerodynamicist to the model designer, to the machine shop, model-maker and instrumentation specialist. Models and test sections will have to be configured for very rapid installation, a multiplicity of data sensors and rapid configuration changes. Data Systems will have

to be re-thought to allow a very efficient real-time transformation of "data" to "information" to "knowledge" available to a design team that may be located many miles from the test facility.

All this calls for much more in the way of behavioral change on the part of the people involved than technology change for the systems involved and in many ways that is the more difficult transformation. Also it must be in place before it can effectively influence the new designs required for the challenges of 2020.

Having identified some of the major issues surrounding the use of wind tunnels in the design cycle, and their effect on model manufacture, we are left with a number of questions surrounding the tunnels themselves:

- Are the wind tunnels of today adequate for the design of the vehicles of the year 2020 - such as aircraft with reduced life cycle costs, extremely long range or high speed vehicles and vehicles that operate at the edge and beyond the earth's atmosphere?
- Will these facilities be used in a different way in the future?
- Is the interaction between EFD, CFD and Flight Testing tomorrow very much different from today?

Of course, the answer to these questions will depend on the type of vehicle that is to be designed. But at the same time we are witnessing a new relationship between EFD, CFD and Flight Testing that will change both the design process and the final result in the future.

3.1.3 Other Scenarios

In the above, the arguments have all been built around the use of the wind tunnel within the design cycle of a particular aircraft requirement; there are other scenarios within which wind tunnels play an important part, for example:

- CFD Validation data
- Fundamental flow physics research for use in creating CFD models
- Research into the performance of new vehicle configurations

In these scenarios, the wind tunnel is divorced from the pressures of the design cycle, and frequently is used with a special experimental rig which would be impractical, or uneconomic to use within the design cycle. Some foreseeable examples of scenarios such as these will emerge in the following sections.

3.2 Future of Wind Tunnel Simulations on Conventional Configurations

3.2.1 Current Assessment

Today wind tunnels are capable of simulating the mainly steady, complex flows over conventional but advanced configurations from low subsonic up to high supersonic speeds (M = 5). This means that new fighter designs, RPV's, transport type aircraft or extremely long range vehicles can effectively be tested over a wide range of model attitudes, or configurations under flow conditions that are representative of the flight envelope. These simulations can be made with a high degree of perfection, thanks to (cryogenic) high Reynolds number facilities, large size wind tunnels that allow the representation of subtle model details, advanced engine simulation techniques and powerful, accurate and high resolution instrumentation. The techniques available today will be further improved in the future, resulting in even better simulations of very complex flows, like engine simulation in ASTOVL configurations including the interaction between the engine exit and intake flows in ground effects.

Present day wind tunnels demonstrate a very high degree of repeatability. Defined as the variation between different tunnel entries for the same configuration, their position within the design process is currently secure. Very often the flight prediction of a new configuration is based on wind tunnel data corrected for differences seen between ground and flight test data on a similar configuration. This practice is less reliable when the current design deviates significantly (in a technological sense) from the "reference" configuration. Once the design margins become smaller, the risk in the design can be reduced further by striving for a better absolute accuracy in wind tunnel testing. To this end it is essential that, in future, we work towards a situation where wind tunnel test results are made fully wind tunnel independent e.g. all possible corrections should be applied to account for differences between the model, wind tunnel, and flight. Back-to-back testing in various facilities and comparison with the results of CFD methods and flight test data conparision with flight data should be used to validate this approach. The FDP has been active in this respect in the past and will remain so in the future.

Simulations are, and will always be, an image of the real world (flight) and not the real world itself, and hence display a number of shortcomings - wind tunnels and wind tunnel test techniques are no exception. However, better wind tunnels will not necessarily improve this situation. Instead the limitations of the present day wind tunnels will be removed largely by combining the test techniques and test results with CFD calculations that either correct the measured results, in many cases in real

time, or actually drive the test execution. Already today store release, as simulated in the wind tunnel, uses the computer in interactions with real-time to define the store trajectory, a process involving CFD derived corrections to overcome deficiencies in the simulation. CFD methods can be, and to some extent already are, used to eliminate or correct for the constraints that wind tunnel walls impose on the flow. Likewise, model support effects or imperfect engine simulations can be corrected with the help of CFD. However, these applications of CFD to wind tunnel testing are today predominantly "far-field" or global effects. The future will show a shift towards more detailed and local CFD derived corrections.

3.2.2 Simulation Inadequacies

The highly non-linear dynamic effects experienced by fighters and missiles are today difficult to predict with the required accuracy. Most existing theoretical prediction methods are limited to linear aerodynamics and subsonic flow. Existing wind tunnel simulations are limited by mechanical limitations of the rigs which make it difficult to penetrate the transonic regime and/or achieve the necessary rates of movement, and result in significant interference between the flow over the model and the flow over the supporting rig. Time accurate unsteady CFD methods today can cope only with limited geometry, and take large amounts of computing resource. This situation will improve but the complexity of the problem and the physics involved necessitates extensive validation. It is vital to obtain reliable experimental data from a specialized rig which can cover the parameter space of concern. This data can then be used either:

- as validation data for an advanced unsteady CFD code when one becomes available, and then use the validated CFD code for all activities within the design cycle.
- to demonstrate that less able CFD codes are able to generate corrections to wind tunnel data collected on practical rigs, and use the wind tunnel to generate the basic data within the design cycle.

Within either of these scenarios, better and more advanced test capabilities are required to generate the reliable experimental data. The Fluid Dynamics Panel has established a number of working groups to stimulate this area.

Another example is the simulation of laminar flow in the wind tunnel. Laminar flow as a means to reduce the drag might very well be a crucial issue for the long range vehicles of the future. However, the extent of the laminar flow region determined by the location transition from laminar to turbulent flow, is in general not well simulated in the wind tunnel due to differences in Reynolds number that alter amplification rates and may result in certain mechanisms not being activated, and flow and surface imperfections that may trigger mechanisms that are not present in flight. Current assessments are that quieter and more advanced wind tunnels are not likely to solve this problem. Instead, existing wind tunnels and flight tests should be used to conduct research to produce a reliable method of predicting the transition location for tunnel and flight; this can then be used either:

- in an absolute sense, by building it into a CFD code and using only this to predict the vehicle characteristics
- or to conduct two CFD calculations, one with each transition position, and use the increment to correct the measured wind tunnel data.

These two examples illustrate how CFD methods might be used in the future to overcome the deficiencies in some aspects of wind tunnel testing. This is only possible when the CFD methods are sufficiently reliable to calculate accurately the difference between two different flow situations. This is turn requires a thorough understanding of the problem and adequate modeling, followed by an extensive validation of these methods for a number of well selected experimental test cases that reflect all the physics involved. New optical measurement techniques will be an essential element in the future to explore the flow in enough detail to secure the necessary standard of test case. As a result of this, wind tunnels in the future will not only be used to validate the design but also to understand and validate the tools that will be used to produce an improved aircraft design.

3.3 Future of Wind Tunnel Simulations for Hypersonic Vehicles

3.3.1 Re-entry Aerodynamics

High speed vehicles (like hypersonic airbreathing missiles) and vehicles that operate at the edge of earth and space (re-usable launchers, re-entry bodies) are to be considered here. The design of these advanced vehicles involves very challenging technologies. Since the design margins are small it is an absolute requirement that the uncertainties involved in prediction methods have well-defined limits.

AGARD Working Group 18 (WG18) was formed in 1988 to address the aerodynamic challenges of re-entry vehicle design. The report on the first part of these activities has been published as AGARD AR-319. The experience of this WG is summarized below.

The necessity and complementary use of CFD, EFD and Flight Testing as discussed (in previous paragraphs) is particularly valid here. It appears very clearly that wind tunnel testing is not going to be entirely replaced by computation, even in the high speed range; but it is obvious that wind tunnel results can only be interpreted through computation at high Mach number. Since both computation and experiment offer only a partial simulation, the flight testing is essential to confirm that all the important phenomena have been correctly accounted for.

The accuracy's obtained from wind tunnel testing in hypersonic conditions are still very poor compared to the present state of the art in subsonic, transonic and low supersonic conditions. Still not enough attention is paid to the calibration of the facilities, which may be explained by a lower level of design activity in this speed range. Furthermore specific difficulties are raised in hypersonic facilities where real gas effects occur. In addition to the traditional flow quality data, the exact knowledge of the physical and chemical status of the incoming gas is necessary. It therefore becomes important to measure the evolution of the flow parameters from stagnation conditions through the nozzle throat down to the test section; using CFD, this information can be used to determine the freestream conditions in which the model is immersed, and then to extrapolate with some confidence to free flight results. In addition, attention needs also to be paid to flow impurities for some facilities whereas for others an important parameter is the duration and steadiness of the flow.

AGARD's FDP WG18 contributed to the calibration of some of the NATO facilities by generating commonly agreed procedures, thus allowing cross-correlation between results from these facilities in comparable test conditions. The spirit of this attempt is similar to the calibration activities of the transonic facilities which occurred years ago within NATO and in Europe. The results are encouraging but testing should be pursued and extended to other facilities.

3.3.2 Propulsion Simulation

For air-breathing high speed (hypersonic) vehicles with RAM/SCRAM-JET propulsion, the simulation of the integrated engine is of crucial importance. There are no facilities available today that can adequately simulate this flow at the required scale. Some smaller facilities are available (AEDC, Russia) that can simulate the inlet-ram/scramjet combination at a small scale. Other existing facilities can be used for a part-simulation of this problem. A research activity exists in the US to prepare for a potential development of the required facilities. Europe still needs to establish its objectives and priorities in this respect. Also in this case the state of the boundary layer (laminar or turbulent) and hence the transition location is of crucial importance for the inlet design: it determines the heat load. An accurate simulation of the transition however will be very difficult to realize. The use of advanced CFD methods to assist these simulations as discussed above is even more required in the case of propulsion simulation but most likely not sufficient, Flight testing, using a flying test bed designed for cost effective testing, is absolutely required to validate the design and to reduce the design risk to an acceptable level. This is particularly required in view of the great sensitivity of the design for small differences in overall engine efficiency.

3.3.3 Thermal Protection Systems

The development and testing of materials that can stand the high temperatures of sustained hypersonic flight and re-entry is an essential requirement for the success of high speed (hypersonic) vehicles and space vehicles. The thermal protection testing facilities used today to quantify the flow interaction with the vehicle surface, rely to a large extent on empirical knowledge. Good correlation can be obtained with existing flight data of some vehicles, but since the interpretation of the flow behavior is approximate, the level of confidence for the flight prediction for a new design remains poor and needs to be compensated by adequate design margins. Here again a calibration operation across NATO facilities would be helpful to establish rigorous comparable test procedures and improve the accuracy of these tests. A proposal has been prepared by FDP for a working group, which will be submitted to the approval of the National Delegates in Spring 1997.

3.3.4 Need for New Hypersonic Facilities

A very wide range of hypersonic facilities have been developed within NATO nations, and most of them have currently a low level of activity. Now additional facilities have become available from eastern-bloc countries, sometimes with good performances and attractive prices. WG18 has made a review of some of these facilities, as well as the instrumentation they employ. The overall impression is that, if each facility is available to any potential user (as is the present tendency), then the hypersonic testing capabilities necessary to solve re-entry type aerodynamic problems are today not limited by the lack of facilities, but rather by the poor accuracy of the results and poor understanding of what is actually measured in these facilities.

Whatever the type of advanced hypersonic vehicles that are developed in the future, it is not going to be possible any longer to cover large aerodynamic testing uncertainties by large design margins. A very important effort needs to be made to understand in

real time the significance of the test data, using advanced measurement techniques and CFD, and to provide more accurate information to the vehicle designers. This means there is a need for implementing, in operational conditions, some measurement techniques which today still remain laboratory capabilities, and to perform a careful, systematic calibration of the facilities. FDP should continue the work initiated in this arena by WG18. Sustained hypersonic flight and hypersonic air-breathing propulsion is a very wide field, which could call for very large new test facilities. However the need for such facilities is closely linked to the nature of the programs which are emerging. It seems we are approaching a time when a clear vision of the civilian programme objectives could be available both in US and in Europe; but a military point of view should be elaborated.

The facilities will be very briefly addressed in the AGARD Spring 1997 symposium on Sustained Hypersonic Flight, both from the point of view of aerodynamic and propulsion. For example, boundary layer transition is going to be a key design issue, but the fundamental phenomena driving transition process need first to be better understood and modelled, before new requirements are placed on facility performance. The propulsion integration issues constitute a whole discipline where multi-disciplinary design techniques play an important role. The validation of the propulsion integration needs to be done experimentally, either on the ground or in flight, and often requires full-scale testing.

It is quite clear that a NATO point of view on future needs in this field has to be worked out in more detail. FDP will direct its activities in this technical area in the future.

3.3.5 Concluding Remarks

Wind tunnels have successfully been used as a tool in aerodynamic design by simulating as closely as possible the flight conditions in a ground based facility. This simulation is often approximate and shows deficiencies, The more complex the flow is in terms of physics involved, the larger these deficiencies will be. Over the last 25 years, new facilities have been built and existing facilities have been improved to better simulate the real flight.

This trend will not necessarily continue. It will not be cost effective to build new, more sophisticated facilities to better simulate the flow. Instead, the quality of the aerodynamic design will be improved in the future by blending the capabilities of experimental (EFD) and computational (CFD) fluid dynamics in an integrated design process. Their complementary role will follow largely from the capabilities and limitations of both techniques to approximate the complete flow.

4. Fundamentals: Developments, Prospects, Challenges

In the realm of fundamental fluid dynamics a number of areas are judged to be of critical importance to the technological goals of the NATO alliance. These areas are reviewed in the following eight sub-sections.

4.1 Transition

A strong international interest in problems of stability and transition in wall-bounded shear layers exists in connection with the design of gas-turbine-engine blades and vanes, low-Reynolds-number vehicles, submarines and torpedoes, subsonic/supersonic civil transports, subsonic to hypersonic aerospace vehicles including missiles and re-entry vehicles. Evidence of this is the number of recent meetings, courses, and workshops devoted to the topic of stability and transition. Various recent AGARD special courses provide important sources of information on the aerodynamic applications of transition.

Understanding transition is necessary for the accurate prediction of aerodynamic forces (lift and drag) and heating and cooling requirements. Moreover, delaying transition by the various techniques of Laminar Flow control (LFC) generally results in lower drag and therefore higher fuel efficiency. It has been estimated that if laminar flow could be maintained on the wings of a large transport aircraft, a fuel savings of up to 25% would be obtained.

Of interest to the turbulence community is the fact that boundary-layer flows are open systems, strongly influenced by and dependent on freestream and wall conditions. Breakdown of laminar flow has been well documented to vary considerably when the operating conditions change. The transition process then provides the vital upstream conditions from which the downstream turbulent flowfield evolves and it is reasonable to imagine that different transition patterns give rise to different turbulence characteristics downstream.

Laminar-turbulent transition is highly dependent on initial and operating conditions. The availability of careful, archival experiments for comparison is the main issue for the validation of theoretical and computational predictions and models: few such experiments exist. The CFD formulations validated to date demonstrate that if the environment and operating conditions can be modeled and input correctly, the computations (nonlinear Parabolized Stability Equations and Direct Numerical Simulations) agree quantitatively with the experiments.

Future challenges for validation include: successful CFD simulations of available complete databases; CFD leadership in the identification, cataloging, and modeling of the effects of freestream disturbances; CFD leadership in the determination of relevant validation experiments for supersonic and hypersonic flows; careful validation experiments and CFD solutions for complex 3-D geometries, and simulations and validations for the high Reynolds numbers and operating conditions of flight.

4.2 Turbulence and Turbulence Modeling

The prevalence of turbulent flow around vehicles and weapons has a strong effect on skin-friction, flow separation, heat or mass transfer, and many other phenomena. It thus has an enormous influence on design and performance capabilities. This has necessitated a broad continuing effort to understand the dynamics of turbulence and to model its effects for flow prediction methods. Although research has addressed the fundamental nature of turbulence from many viewpoints, neither a universal theory of turbulence nor any widely applicable turbulence models have been achieved. With the continuing increase in computing power, the deficiencies of turbulence theories and models constitute the critical roadblock in the way of routinely obtaining reliable flow predictions by use of computational fluid dynamics (CFD). (ref: sec. 2.5)

Today, though the search for a universal theory of turbulence has not been abandoned, theoretical efforts are also focused on a variety of other goals. Among these are efforts based on the hypothesis, not yet proven rigorously, that turbulence has properties like those of simpler nonlinear dynamical systems though of a complex spatio temporal nature. Indeed, numerical simulations of turbulence have been utilized to identify characteristics which are amenable to control much like the simpler nonlinear systems such as vibrating beams or the heart. Research continues on such control concepts which may be linked, then, to other developments like microelectromechanical systems (MEMS) to provide spatial and temporal control inputs to the turbulence. Such applications are projected to be of major importance in the first decade or so of the twenty-first century, leading to dramatic improvements in boundary layer control, heat and mass transfer, and other flow processes.

The practical need to incorporate the effects of turbulence in descriptions of fluid flow has driven the development of a wide variety of parameterizations or models. These range from simple algebraic descriptions to complex representations based on partial differential (transport) equations. These equations are solved together with the averaged general equations of fluid mechanics (Navier-Stokes equations) to arrive at a prediction of a flow field. None of these turbulence models has been found capable of representing a wide range of the various types of flow encountered in practical situations: attached boundary layers; separated regions, vortices, shocks, jets, etc. In practice today models are selected or developed for a particular problem and utilized in a restricted range of parameters and geometries. It is important to continue the search for more sophisticated turbulence models which can address a wider range of flows. As model sophistication increases over the next decades, the computation of viscous flow around entire vehicles, including maneuvers, will become commonplace.

Since the dynamics of turbulence is contained, in principle, in the Navier-Stokes equations, an alternative to finding a separate theoretical description or to modeling the effects of turbulence is direct numerical simulation (DNS). DNS involves direct computation of the turbulence by integration of the non-averaged Navier-Stokes equations. This is extremely demanding of computer power so DNS will be limited to simple flow configurations and to low Reynolds numbers (small scales and low speeds) for the foreseeable future. However DNS results are now considered valid enough to complement experimental data. DNS results describe the flow at any instant and location and at all scales of motion and are thus extremely valuable for the development of turbulence models which can be used for practical configurations and scales. A variation of DNS is large-eddy simulation (LES) which models the small (more universal) scales of motion and directly computes the larger eddies. The demand for computer resources is thus much less than for DNS and the variety of addressable geometries and scale sizes is expanded. LES has the potential to become a major practical tool by the year 2020.

Experimental research on turbulence has benefited immensely from improvements in instrumentation over the past several decades. Nonintrusive optical techniques such as Laser Doppler Velocimetry (LDV) and particle image velocimetry (PIV) have revolutionized the acquisition of detailed databases for the understanding of turbulent flow and for testing turbulence models. LDV in particular has provided velocity measurements in formerly inaccessible regions such as in turbomachines and in hazardous or high temperature media. It also can provide critical data in separated flow regions where other techniques fail. Whereas LDV can provide time records at a given point, PIV can provide velocities over a plane at an instant. This is advantageous in flows containing coherent motions, such as vortices, where correlations between locations are needed.

Below a freestream Mach number of about 5 the Mach number of the turbulent velocity fluctuations is less than 1 and compressibility affects mainly the mean flow field, not the turbulence. If interest continues in hypersonic flight (Mach no. >5), however, complex phenomena such as turbulence shocks, acoustic damping, and complex local Mach cones, must be addressed. The turbulent flows over hypersonic vehicles will require new approaches for measurement, prediction and control.

Research on turbulence is continuing on many fronts. Theoretical descriptions based on advances in understanding nonlinear dynamic systems may be useful for control of turbulence. Statistical theories, such as renormalization group theory, are being used to derive advanced models of turbulence. New instrumentation such as holographic particle image velocimentry and sophisticated small-scale models for large-eddy simulation promise to further our insights into turbulence. These and other advances will continue to provide improved descriptions of turbulence and its important effects on fluid flows essential to a board range of technologies.

4.3 Separation, Dynamic Stall and Unsteady Vortical Flows

Boundary-layer separation and consequent stall during flight are problems of broad general importance. These concerns are particularly important to missions involving fighter aircraft and missiles during combat maneuvers. Unsteady, three-dimensional separation involving strong vortices is a feature of the flow in these applications.

Agility is essential for survival of combat aircraft and it involves flight and rapid manoeuvreing at high angle of attack (HAOA). The term "agility" means the "ability to move from one maneuver condition to another at a rapid rate". It is anticipated that advanced tactical maneuvers will occur at angles of incidence higher than the dynamic leading-edge stall limit (post-stall maneuvering, PST). In particular, angles of attack greater than fifty degrees and Mach numbers ranging from 0.05 to 0.2 will characterize the PST regime. It is expected that PST conditions will persist for no more than say five seconds. Obviously PST maneuver performance will depend heavily upon available control power in pitch, roll, and yaw, and on dynamic response.

Development of more agile combat aircraft will require detailed knowledge of vortex behaviour, vortex asymmetry, vortex breakdown, and time lags involved in the changes in the vortical flows as the aircraft manoeuvres. Attainment of sufficient accuracy in prediction of HAOA dynamic behaviour of combat aircraft will require that the various non-linear and time-dependent effects be correctly represented in the mathematical models, replacing the mainly linear methods used at present. Much improved modelling of vortex breakdown position and movement in highly unsteady conditions will be necessary. Another requirement is alleviation of wing rock. This rather debilitating phenomenon often occurs when flying in the intermediate AOA range (about 30^{o} to 50^{o}.) Active control methods should be explored, for example pulsating blowing or use of microelectromechanical (MEMS) actuators near and around the wing leading edge to control the 3-D separations and attendant vortices responsible for wing rock. Thrust vectoring is effective for providing lateral control at HAOA where conventional control surfaces lose their effectiveness. However a more elegant approach, probably involving fewer compromises, is forebody vortex control. This basically involves control of the 3-D flow separation from the aircraft's forebody.

By taking advantage of some of the characteristics of the dynamic-stall process, one can conceivably enhance vehicle performance. The large amounts of lift and drag generated prior to shedding of the dynamic-stall vortex are desirable (these levels are higher than the corresponding static case). The control of this lift and drag is the topic of much research currently in connection with supermaneuverability. One essential need is the ability to assure predictable flow characteristics. Knowledge of the state of the boundary layer at incipient stall is essential.

Dynamic stall can also degrade vehicle performance. For example, for helicopters, high-speed flight and maneuverability are seriously impaired by retreating-blade stall. The large cyclic pitch variations required in forward flight result in large surges followed by collapse in lift and negative pitching moment on the blades. The attendant large impulsive loads on the blades cause strong vibrations which result in severe vehicle and crew fatigue. Consequently complete stall prevention, by control of the blade boundary layer behavior, would be desirable in this case.

Areas of research in connection with unsteady flows that are currently active include: numerical-technique development, viscous-inviscid interaction, and experimental observation. In predicting stall, current methods include Navier-Stokes solvers and vortex-dynamics methods. The need for accurate solutions of the time-dependent three-dimensional vortical wake, the nonlinear effects inherent in large-amplitude motion, the trailing edge conditions, and the viscous corrections which depend strongly on the unsteady pressure distribution complicates and hinders trustworthy prediction techniques. To this end, one important physical aspect that needs to be modelled accurately is laminar-to-turbulent transition. Laminar separation with subsequent transition can occur. Measurements of transition in separation regions are very difficult. There remain

many uncertainties in the recovery region of separation bubbles. The accurate prediction of transition location and length can have a very significant influence on vehicle performance.

4.4 Interaction of Separation and Transition

Numerous applications such as flight at high angle of attack (HAOA), cavity flows related to weapons release, laser detection and stand-off weaponry, leading edge separation control and multi-element lifting surfaces involve the interaction of separation and transition (IST) from laminar to turbulent flow. Improvements in these areas will lead to important gains in military and civil aircraft performance.

HAOA exemplifies the intense attention that these applications have received by AGARD and the various NATO nations over the last twenty years. However, they are not widely recognized as IST problems. Forebody vortex control and dynamic stall associated with HAOA have defied experimental and computational simulation and will continue to do so without strong interaction with theoretical models. Poor understanding of the underlying IST (possibly chaotic and bifurcating) flow physics prevents designers from making effective trade-offs needed for optimum vehicle performance.

Challenges in treatment of this class of problems are that they are unsteady, nonlinear, and require understanding of scaling issues from the laboratory to flight. For the transition aspects of IST problems, difficulties are the combined effect of non-parallelism and reverse flow associated with the separation as well as the lack of suitable experimental databases. Bright spots in our arsenal of techniques are direct simulation, new optical diagnostics, advanced algorithms using massive parallelism and adaptive, unstructured grids and combined asymptotic and numerical (CAN) methods which successfully integrate theoretical and computation viewpoints. In addition, advances in microelectromechanical systems (MEMS) offer the possibility of miniaturized sensing and control devices (possibly with neural networks in sensitive high leverage regions such as nose tips and wing leading edges. Application of this technology must be made in a "smart" mode by combining it with understanding obtained from theory, computation and experiments.

It is reasonable to expect that by the year 2020 substantial advances can be made in IST problem areas. Advances could lead to envelope expansion of supermaneuverable fighter aircraft from subsonic to transonic speeds and higher angles of attack, and reduction or elimination of adverse HAOA characteristics such as wing rock, yaw departure and helicopter blade flutter. This could drastically improve safety, mission survivability and reliability and lead to reduced cost. Improved understanding of cavity flows could result in reduced certification cost and better targeting accuracy and could yield reliable weapon and fuel tank separation from the parent vehicle. It could also lead to successful airborne laser concepts using flow control schemes and reduction of density fluctuations and noise.

4.5 Shock Wave/Boundary Layer Interactions

In aeronautics, shock wave/boundary layer interaction has been of interest since the early 1940s when it was discovered that a supersonic flow field could be greatly affected by interaction between the almost inevitable shock waves and the boundary layers developing on the vehicle surface. This effect is spectacular on transonic airfoils because of the great sensitivity of such flows to any change, even small, in the boundary conditions. In this case, the existence of a shock in the inviscid portion of the flow field affects the viscous part of the flow, possibly causing large displacement of the shock wave itself with further deep repercussions in the viscous regions. This phenomenon, called strong viscous/inviscid interaction, plays a key role in the performance of modern transport aircraft. These effects may have catastrophic consequences if the shock is strong enough to cause separation of the boundary layer flow, leading to loss of lift, dramatic increase of drag and occurrence of buffeting. Shock wave/ boundary layer interactions also play a vital role in supersonic air intakes where they reduce the efficiency and can be the root cause of intake buzz or unstart. It is also important in many other applications including over expanded nozzles, control surfaces and turbo machines. At hypersonic velocities, shock induced separation is particularly troublesome because it is accompanied by intense heat transfer to the surfaces because of the flow high enthalpy.

In two-dimensional flows the physics of the interaction are well understood and the influence of the key parameters clearly identified. Although a large quantity of experimental results is now available, the situation is less satisfactory for three-dimensional interactions. Three-dimensional supersonic and/or hypersonic flow fields most often contain shock systems leading to complex patterns involving multiple shock/shock interference coupled with shock wave/boundary layer interactions. Physical understanding and prediction capabilities for such flows are still limited. Nevertheless, the spectacular progress in numerical techniques during the past 30 years has led to the development of efficient predictive methods. In principle these enable good predictions of complex flows, including multiple interactions. Adequacy of turbulence models can be a problem however; even the most advanced turbulence models give poor results when

separation occurs. Available turbulence models are generally deficient in predicting the strong history effects taking place in an interaction because of the rapid retardation of the flow.

As in other areas of fluid dynamics, Laser Doppler Velocimetry (LDV) has enabled good data banks to be compiled to aid understanding and validation of computational models. The unsteady effects associated with shock wave/boundary layer interactions have been the subject of a very limited number of investigations. The mechanism leading to large scale fluctuations, like buffeting, is not really understood. Also, the possible coupling between shock oscillations and turbulence remains an open question.

Since one has to live with shock waves and boundary layers, control of the interaction phenomenon must be seriously considered. Control seems indispensable on laminar flow profiles to avoid extended shock induced separation. Also, shock control is envisaged for air intakes at high Mach numbers. The techniques can be passive or active, with fluid manipulation or surface deformation. Development of closed loop systems with adequate sensors and actuators is envisaged.

Shock wave/boundary layer interactions will remain a subject of major concern in the coming years, particularly with regard to hypersonic flight. Extensive continuing research is warranted.

4.6 Aerothermodynamics

4.6.1 Introduction

The classical design procedures for vehicles flying even at high supersonic Mach numbers around 3 are conventionally restricted more or less to minimising the wetted surface of the vehicle and therefore to minimise the drag in order to achieve maximum performance with regard to maximum range (civil/military transport) or maximum manoeuvrability or excess thrust (fighter). For vehicles flying at hypersonic speeds in addition the aerothermodynamic heating plays an even more important role for the selection of adequate materials and design of structures. In addition to mechanical (aerodynamic) loads the heatloads have to be taken into account. Heatloads are understood to include three major components (for details see Ref.[1]):

- Equilibrium (adiabatic) wall- temperature,
- Heat fluxes (heat transported through the wall, depends on the choice of materials and structures) and
- Total amount of heat accumulated versus time in the vehicle (depends on the Vehicle's "Heat Sink" potential)

[1]) E.H. Hirschel, "Aerothermodynamics of Radiation-Cooled Surfaces", AGARD R-813, 1996

Due to the lack of representative experimental flow simulation in existing ground test facilities the prediction of these three components relies mostly on CFD.

Three major classes of flight vehicles are mainly considered for flight with hypersonic speed in the atmosphere:

1.Re-entry vehicles (e.g. fully reusable space transportation systems)

2. Hypersonic cruise vehicles (e.g. Missiles)

3. Accelerated vehicles (e.g. space transportation system during ascent)

The typical flight regime for these three different classes of vehicles is shown in **Fig. 1** depending on flight altitude and speed.

Two major design tasks are related to the problem of aerothermodynamic heating for the development of hypersonic flight vehicles:

- Highly Reliable Heatload Prediction Techniques
- Successful Heatload Minimisation as part of an overall "Heat-Management" Strategy

4.6.2 Heat Load Prediction Techniques

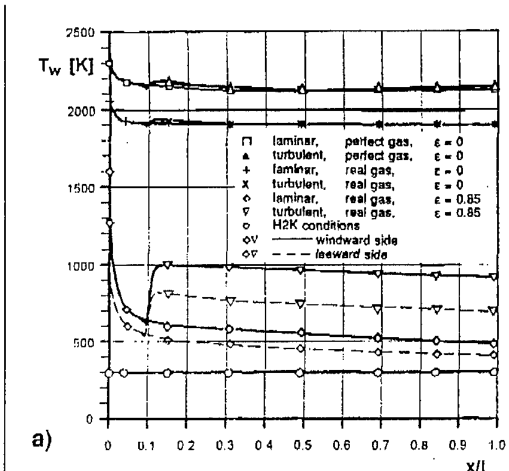
The most important task for the prediction of the aerothermodynamic heatloads on a vehicle flying at hypersonic speed in the atmosphere is the prediction of the wall temperature at its surface. This temperature depends first of all on the balance between the part of total heatflux of the gas penetrating the structure and the part being radiated back from the surface and therefore on the assumptions which have to be made for the materials properties e.g. radiation emissivity and surface catalycity. But in addition the total heatflux depends on the state of the boundary-layer, laminar or turbulent, and therefore also on surface properties e.g. roughness and geometric irregularities which influence the transition from laminar to turbulent flow. In most design cases the part of the heatflux penetrating the wall is set to zero. This decouples aerothermodynamic and structural interaction and leads to the definition of the adiabatic "Recovery" wall temperature which depends only on the amount of heat being reflected by radiation on the (hot) surface.

Fig. 2 demonstrates the influence of the assumptions for the state of gas (perfect or real gas), boundary-layer (laminar or turbulent) and heat radiation

specified by the emissivity ε on the local adiabatic recovery wall temperature and the skin friction coefficient which contributes significantly to the overall vehicle drag. The example is typical for the symmetry line of the fuselage of a representative vehicle flying at Ma = 6.8 at 35 km altitude according to Ref. [2]). In addition the result which could be obtained by a typical "cold" wind tunnel test facility (H2K, DLR, Cologne) is shown.

Three major conclusions can be drawn from this systematic compilation of data:

1. Unrealisticly the windtunnel test facility will give unrealistic low wall temperatures and unacceptable high values for the friction drag.
2. The effects of heat radiation will lower the wall temperature to a level which is needed with regard to materials and structures for flight at hypersonic speed in the atmosphere.
3. The state of the boundary-layer, laminar or turbulent, and the transition location may contribute significantly to drag critical (cruise) vehicle feasibility.



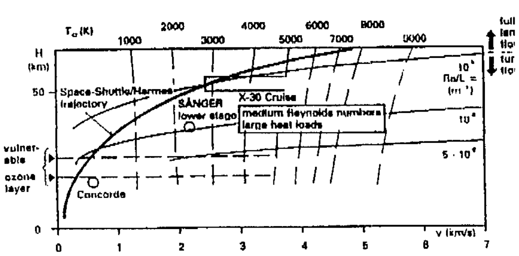


Fig. 1 Total Temperatures and unit Reynolds numbers as a measure of overall heatloads versus speed and altitude

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[2]) Schmatz M.A. et all, "Numerical Methods for Aerodynamic Design II", Space Course Aachen, 1991.

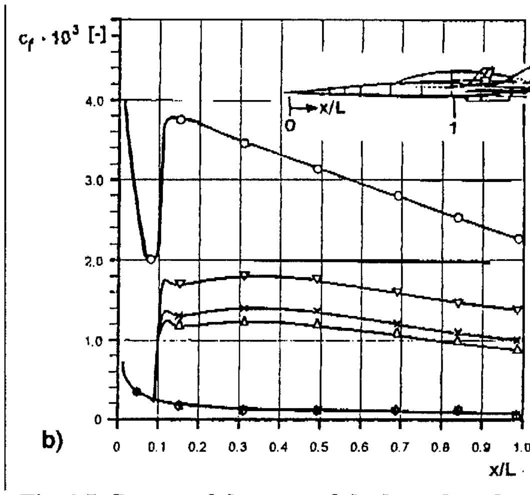

Fig. 2 Influence of the state of the boundary-layer (Laminar/Turbulent and radiation cooling) on a) wall temperature, b) skin friction. Symmetry line of SÄNGER forebody, $M_\infty = 6.8$, Re = $1.22 \cdot 10^8$, L = 55 m, α = 6°, Ref [2])

4.6.3 Heat Management Strategy

Surface heat radiation has been shown to be a highly efficient "Passive" cooling means. If the heatflux penetrating into the wall is not equal zero, Diagrams like **Fig. 3** can be used to estimate the amount of heat transfer (KW/m^2) needed (at constant wall radiation with ε = 0.85 assumed) not to exceed a selected maximum design wall surface temperature with respect to a selected material. Therefore the effect of radiation cooling has to be calculated for any vehicle as a function of Machnumber, emissivity and heatflux allowed to penetrate through the wall structure. For a typical hypersonic flying testbed, "HYTEX" (means hypersonic flight experiment) this has been done during the German Hypersonics Technology Programme (1987 - 1995).

Fig. 3 gives a survey on the results.

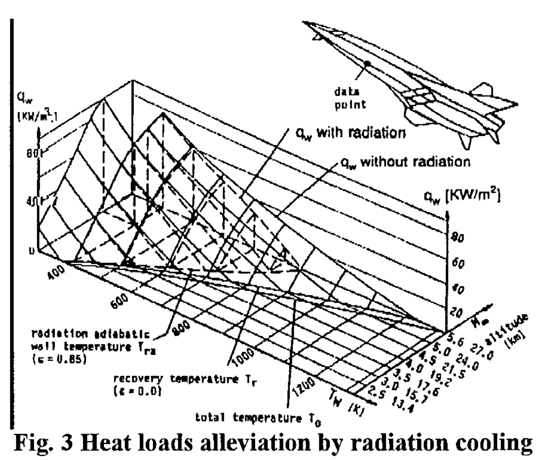

Fig. 3 Heat loads alleviation by radiation cooling with ε = 0.85 on the lower symmetry line of a typical hypersonic flight test vehicle at x = 5 m, α = 5° and turbulent flow.

The adiabatic recovery wall temperature can be found at the bottom plane representing zero heatflux q_w through the wall. Even at moderate hypersonic speed of Mach = 5.6, the effect of radiation cooling on the wall temperature amounts to nearly 350K. This means, that the vehicle could fly with a metallic "Hot" structure at a maximum temperature of about 900K.

The amount of heatflux going into the structure has to be integrated to get the accumulated heat which has to be balanced against a heat sink capacity of the flight vehicle during its whole flight path. The overall heat management for a vehicle flying at hypersonic speeds requires a very carefully developed strategy to balance all heat sources with the available heat sinks as **Fig. 4** shows schematically. But first of all the total amount of heat being transmitted through the surface of the vehicle must be minimised using the effect of radiation cooling.

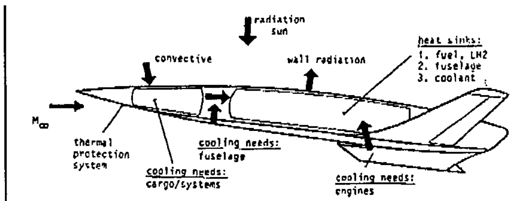

Fig. 4 Heat sources and heat sinks for a vehicle flying at hypersonic speed, Ref. [3]).

4.7 Reynolds Number Scaling

Reynolds number and Mach number are the two aerodynamic similarity parameters which relate wind tunnel test data directly to flight conditions.

Reynolds number scaling refers to techniques used to predict high (flight) Reynolds number aerodynamic parameters, such as force and moment coefficients, from low Reynolds number experiments. These scaling techniques can be experimental, analytical, or a combination of both.

Reynolds number scaling is necessary because most wind tunnels used for development testing have a maximum Reynolds number capability far below flight values (often an order of magnitude lower than flight). An example of Reynolds number scaling is boundary layer tripping in low Reynolds number tests, used together with analytical corrections to predict skin friction for flight conditions. This technique is limited to flows where the inviscid portion of the flow field is relatively insensitive to the effects of the boundary layer. Generally, this is not the case where strong inviscid/viscous interactions are present, such as from shock/boundary layer interactions and flow separations. In these situations, the flow field is exceptionally complex and difficult to produce experimentally at low Reynolds number for scaling to higher Reynolds number. Also the viscous/inviscid interactions can be strongly dependent on "tunnel effects , i.e., wind tunnel wall interference, free stream turbulence and noise, spatial and temporal variations in the flow, etc. which produce what is termed pseudo-Reynolds number effects.

The development of analytical and experimental techniques for Reynolds number scaling is in its infancy. There is a strong need to reduce performance prediction uncertainty due to Reynolds number scaling problems in the design of both military and commercial aircraft. Future high performance military aircraft are expected to be low observable and highly maneuverable. This combination of qualities is not necessarily compatible for performance purposes and leads to the expectation that accounting for Reynolds number effects will be an even greater concern in the future than in the past. For range, payload, and operational economy reasons, a similar conclusion can be reached for future large aircraft such as transports.

Conventional low Reynolds number wind tunnels are expected to carry the experimental workload for aircraft development for many years to come. Even with the potential that highly productive higher Reynolds number conventional wind tunnels may be built, these will still be considerably short of flight Reynolds number simulation for many situations. Cryogenic wind tunnels such as the NASA NTF, the European Transonic Wind Tunnel (ETW), and the German KKK low speed wind tunnel produce near flight Reynolds number, but such wind tunnels are low in productivity and are not expected to be able to adequately serve workload needs. These facilities, however, are invaluable for understanding Reynolds number effects on complex flow fields and developing Reynolds number scaling procedures.

The expected trend is also toward more use of computational fluid dynamics (CFD) in Reynolds number scaling. Applicability of such tools will be driven by adequacy of the flow physics modeling, especially that related to boundary layer transition and separation. Much research is needed to improve, develop, and verify CFD tools. In the Reynolds averaged Navier-Stokes (RANS) formulation, a major hurdle is adequate turbulence modeling. This will be an ultimate pacing item in our ability to adequately use CFD for complex flows exemplified by shock/layer interactions in two and three-dimensions, unsteady phenomena and the interaction of separation and transition. Direct Numerical Simulations (DNS) could be the ultimate

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[3]) E.H. Hirschel, H.A. Haindl, "Aerothermodynamics Analysis Tools and Strategy for the the design of Reusable Launch Vehicles", Dasa-LME12-S-STY-188, 1996.

tool to complement wind tunnel and flight testing; the trend to faster computers, massive parallelism and faster algorithms may make application of DNS to realistic configurations practical in the next fifty to one hundred years. It could also lead to better turbulence modeling and closure for RANS schemes as well as improved Reynolds number scaling techniques. Such advances could translate into substantial gains in aircraft performance and economics, even by the year 2020. Cooperation between the NATO countries would almost certainly accelerate progress.

4.8 Favorable Interference

Stable and efficient performance of aircraft depends on the proper design of the components. In general the wing dominates the characteristics of the configuration and the other parts give additional contributions. These may be negative or they be positive and improve the overall lay-out and behavior. The latter effect is called favorable interference. There are well known and well exploited favorable interference effects, but there are others which need further investigation.

A well known favorable interference effect is the main wing/horizontal tailplane interference. The downwash of the main wing reduces the effective angle of attack for the tailplane so that it still has attached flow when the flow over the wing separates, a prerequisite for stable flight in every flight condition. A favorable interference of wings which has not been exploited is the canard forward-swept wing interference which alleviates the premature separation in the forward-sweep-kink. Close-coupled wings which are vertically/ horizontally staggered offer potential. Winglets attached at wing-tip have by far not reached their optimal form. Further-more the so-called Busemann wing for supersonic flight offers considerable advantage.

A large field of favorable interference is the exploitation of vortex flows, a field that is especially of interest for combat-aircraft. For example, a close coupled canard induces a downwash on a delta wing which allows the aircraft to go to a higher angle of attack in a maneuver situation. Another example is a leading edge extension which fixes the body vortex at high angle of attack and removes an early buffet.

Another field of favorable interference is the proper exploitation of engine-airframe interference. Propellers have higher thrust when operating in a retarded flow. Thus, proper arrangement of pusher propellers produces a favorable effect. Upper surface engine inlets are relatively insensitive to changes of angle of attack due to the alignment of streamlines on the upper surface.

A very important effect which has to be exploited for high speed vehicles, especially wave-riders, is the use of the pressure-recovery on the lower side. This pressure increase generates the lift, and gives at the same time when properly designed the pressure recovery which is necessary for the air-breathing engine in hypersonic and supersonic flight. Wing-wing interference and wing-engine interference effects are of great importance for long endurance aircraft. Proper pressure recovery on the lower surface of the wing has considerable importance for SST and TOTS configurations with air-breathing engines.

5. Summary

Continued research in Fluid Dynamics will be necessary in order to realize the affordablity goals that NATO is discussing for future systems. Whether the medium be water , air or real gases, fluid dynamics is the technical area that determines the external shape and controlability of the vehicle to satisfy the design mission requirements. Designing the vehicle correctly the first time has an enormous influence on the total design cycle. In addition, the accurate determination of vehicle performance, controlability, and loads through continued improvement in Computational, Experimental and Fundamental Fluid Dynamics, will allow design margins in other technical disciplines (ie. Structures, etc.) to be reduced thereby providing the most economical integrated design.

Flight Vehicles Panel

Contents

Future Transport Aircraft (FTA)

(Tactical Transport Intermediate Range)

Klaus Wieland

1. General

At the beginning of the next century - starting from 2005 - the aged European tactical air transport fleets mainly consisting of C 130 and C 160 aircraft have to be replaced by modern equipment. This becomes urgent because of the increasing maintenance effort and associated cost as well as the change of military air lift scenarios following the breakdown of the Soviet Union.

The existing aircraft are characterised by relative small cargo hold dimensions and low cruise speeds and they are only capable lifting fractions of the equipment to be deployed. The remaining parts have to be transported by either rail or ship increasing the time needed (Fig. 1).

The increased airlift capability of the future tactical airlifter must therefore be superior to the existing airlifters and cover at least 25 tons over 2000 mm or 32 tons at reduced range and a cruise speed in the range of Ma = 0.7. The cargo hold dimension must be increased to comfortably load all the critical goods out of the inventory most of the European forces. 8 European air forces interested in a new tactical air lifter have meanwhile (May/96) established the European Staff Requirement (ESR) for such an aircraft.

Essential elements therein combine a reasonable high cruise speed (M_{CR} = 0.68) with the capability of extremely slow speeds for airdropping missions not higher than 130 Kts. At the same time there are limits on the main dimensions of the new aircraft to allow the usage of existing infrastructures (hangars, ramps, etc.).

As a consequence, the aero-design of the new tactical air lifter must combine excellent efficiency in the high and low speed regime at wing area loading factors nearly two times higher than with the existing aircraft. This requires the development of a highly efficient high lift system where the application of blown flaps must be considered necessary. In Europe there is more or less no experience with turbofan blown flaps for high lift augmentation (as on C17 in the US). Quite reasonably turbo propeller-engines shall be taken into account being a viable alternative.

For a programme reaching out into the next century with a planned IOC (Initial Oper. Capability) in 2005 and a system life of at least 30 years, most modern material- and structure technologies must be employed. Whilst modern civil air planes in these days employ about 20% fibre reinforced structures, this fraction may be increased to 35% on the tactical airlifter, if the wing primary structure could be build from carbon fibre reinforced plastic materials (CFRP).

Based on various positive experiences in the civil aviation (example: large empennage structures in the

Airlift parameters

Aircraft	Average payload (tons)	Sorties (tonnage)	Percent Airlift
FTA	23.5	1.228 (28.902)	100%
C130	12.5	1.386 (17.301)	60%

Assumed fleet size = 150 aircraft

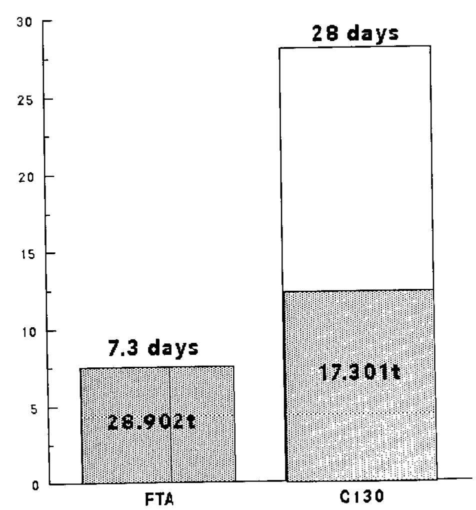

Fig. 1: Comparison of FTA and C130 on typical Reaction Force Deployment

Airbus world), such application to a wing box of the FTA should prove successful and is promising in terms of weight saving, fatigue and corrosion resistance. However, the compatibility with threat environment (battle damage tolerance) must be proven as well.

The mission profiles of the future tactical airlifter will contain low level flight segments. The objective is to fly as fast as possible and as close as possible to the terrain to avoid ground and air threats. The fraction of low level flights may be in the order of 25% out of the total life time. The transposition of these elements to aircraft capabilities is a challenge for structure and systems.

The aircraft structure will be subject to an increased number of load cycles due to gusts and manoeuvres in low level flight. Especially on the wing there will be essential benefits regarding fatigue of the structure if CFRP will be used.

On systems side an advanced and redundant flight control system including a low level autopilot function a highly accurate navigation system and an accommodated man machine interface is required.

The mission management system of the new airlifter must fulfil the requirements for jamfree, autonomous and passive navigation to enable high accuracy air land operations as well as autonomous landings. Automatic flight on preplanned routes including low level flight segments should be possible. Digital terrain information is a definite candidate for distortion free navigation sensors. In combination with other navigation sensors (GPS, IN), very high accuracies with at the same time high reliability should be achievable.

The future European tactical air lifter will be realised by the Airbus-Consortium. Well established structure- and manufacturing technologies as well as an international proven development process will guarantee creation of a highly performing but cost effective basic tactran aircraft. This basic aircraft shall at least be capable of being updated by the individual nations air forces with their options for special systems and functions. As a prerequisite, the basic aircraft as carrier should incorporate all the technologies to enable the basic functions:

- High speed, high altitude, long range deployment;
- Full tactical air drops/air land/soft field performance;
- Manoeuvre capabilities for autonomous ground operations;
- Operation in hostile environment and adverse weather;
- Low maintenance structures and basic systems.

2. The main elements in the development of the future European tactical air lifter

2.1 The application of carbon reinforced plastics for the wing primary structure

The application of such material and structure technology for aircraft primary components in civil aviation has proven a weight saving potential of more than 20%. However, such materials offer on top of weight savings, which are sensitive to performance and overall operating costs, excellent resistance against fatigue and corrosion. Both elements are beneficial for life cycle cost because they will reduce maintenance remarkably comparing with conventional metallic structures. However, for military operations in hostile environment with bullets and warhead fragments it must be proven that CFRP does not behave worse than aluminium to qualify for application.

CFRP-laminates offer design optimisation potentials using layer compositions to reduce cracks on impact as well as aeroelastic tailoring. Aeroelastic tailoring offers the tuning of directional material characteristic (stiffness) enabling better control of wing flutter at high speeds as well as whirl flutter caused by propeller engines or big turbofans mounted on wings of high aspect ratio.

The required life time for the future tactical air lifter will be 30 years (by experience from the existing transport fleets it will be much more) consisting of 10.000 major cycles by 25% low level flight time.

CFRP has proven its capabilities and maturity being applied to many prime structures in civil aviation. There should be no risk to apply this material on a military transport on the wing primary structure at the next convenience.

2.2 Development of a Turboprop-Engine for Cruise Speeds up to M = 0,72

The request for a relative high Mach-capability (greater M + 0.7) and simultaneously extreme low speed capabilities(paradropping) combined with excellent autonomous ground operations (reversing without truck assistance) call the "old turboprop" back into the favourite position for application. Unfortunately, there is more or less no experience in the western world as far as the speed range and the required power class are concerned. In civil aviation, there are turboprops in operation up to M=0.6 (Saab 2000) and installed power up to 4500 SHP. The future tactical airlifter will have a max. take-off weight of more than 100 tons (compared with 49 tons of Transall C160) and will be powered by 4 engines in the power class of about 9000 to 10.000 SHP. For this power class, no power plant will be

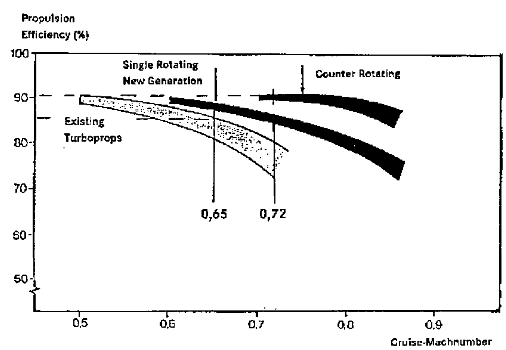

Fig. 2: Propulsion Efficiency versus Speed

available off the shelf and must be developed inclusive gearbox and propeller. To avoid excessive development cost, the use of existing core engines from the market must be considered.

Selecting the propeller concept, the choice is between single rotating and counter rotating systems.

Counter rotating systems offer excellent propulsion efficiencies up to high Mach-numbers (see Fig. 2) and consequently low specific fuel consumption. The system weight is considerably high and the propeller control system is of high complexity (maintenance sensibility). There is hardly any experience available in the western world for such systems. Developments to higher subsonic cruise speeds (prop fans) have not found application so far because of noise problems, low fuel cost and generally high development risks.

Single rotating systems are of considerably simpler design, lighter weight and rely on the experience of decades of service life, however in remarkably lower power classes than required for the future tact. airlifter. The propulsion efficiency is about 5% lower than on counter rotating system and the propeller slip stream is characterised by residual swirl which is a penalty for the design of the propeller slip stream wetted areas of the aircraft wing (e.g. the lift distribution).

In any case, the final choice must reflect development risks, development cost and life cycle cost. All in all, there are good chances for the single rotating propeller to win the competition..

2.3 Aerodynamic Design and Propeller/Wing Integration

The aerodynamic design of the future tactical airlifter has to cover a wide range of aspects. Wing design both at high cruise machnumbers of $M_{cr}= 0.68$ and low speed to achieve good field performance and paradropping capabilities must be studied together with wing engine integration for the case of a turboprop application. High lift vs. drag (L/D) values must be achieved and the interference drag from engine installation and wing interaction must be minimised.

The aircraft is also required to have the capability to cruise at $M_{Mo} = 0.72$. Consequently, the wing design will show a moderate sweep angle and should utilise transonic profile sections which guarantee acceptable increase of the compressible drag beyond the cruise speed design point M_{cr}=0.68. Special care must be given to handle the propeller slip stream and in the case of a single rotating propeller also the swirl. From combination of swirl and slipstream on a swept wing asymmetric effects on lift (see Fig. 3.), moments and drag are expected and have to be minimised.

To fulfil the demanding requirements in the low speed regime, an efficient high lift system must be developed.

High lift coefficients c_L=2.65 (power off) and greater C_L=4 (with power effects) have to be established. This can be achieved by a double slotted flap system which is "blown" by the engine/propeller slipstream. Fig. 4 (following page) shows the effect of this principle on aircraft speed depending on engine power and flight path angle.

Demonstrated alternatives of the blown flaps principle are:

- a flap system directly blown by the very powerful jet of a turbofan engine (applied on C17);
- the traditional propeller blowing with moderate power and the slipstream widely spread over the wing and the flap system.

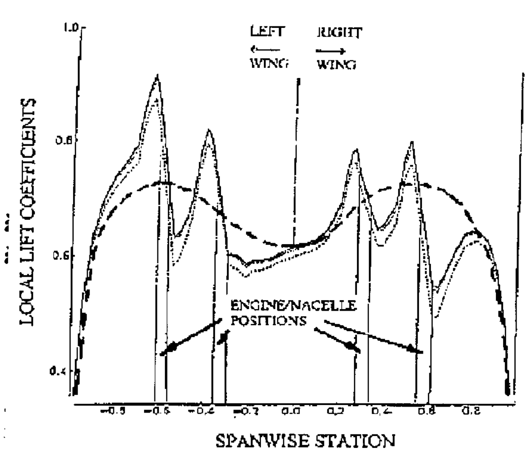

Fig. 3: Spanwise Lift Distribution caused by Propeller Swirl

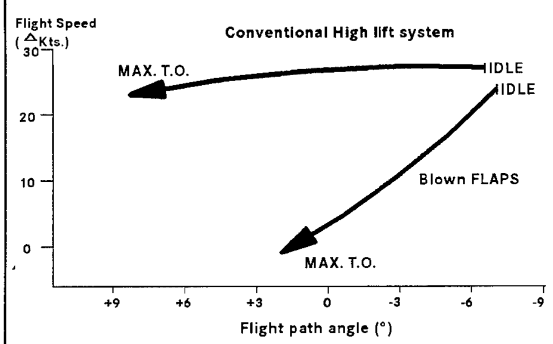

Fig. 4: Low Speed Benefits from Blown Flaps Flaps in Landing Configuration

The first solution is technically very demanding, leads to a heavy lift system and structures and is only reasonable if the application of a turbofan engine is required for other reasons (high cruise speed, comfort, low maintenance etc.). Experience on such systems is only available in the US and consequently has been transposed to the design of the C17.

The second solution would avoid challenging technology-programmes and can be established in the development time frame of the future FTA. Evaluations on first principal wind-tunnel models have already proven the feasibility of the set design objectives, however much work to improve and optimise this technology must still be done.

This requires development, manufacture and testing of a wide range of wind-tunnel models where special care must be given to the most accurate simulation of engine power and propeller slipstream. The necessary propeller simulation technique can be developed from the existing state of the turbofan simulators but multi component balances must be installed in the rotating propeller hub to identify the resulting propeller thrust vector which more or less is never perpendicular to or in the centre of the propeller disc. Sophisticated calibrations of such model propellers need to be performed unless testing in expensive wind-tunnel facilities can commence.

Beside the demand to establish a high aero-standard of the wing it must not be forgotten that the fuselage of a tactical air lifter with cargo ramp and doors at the rear has a high drag potential. A satisfactory compromise between loadability and aerodynamic qualities has to be achieved.

Last but not least, a low drag configuration for the landing gear fairings has to be developed. Operations on unprepared runways require a great number of big sized wheels for the main landing gear. This gear will likely be installed in nonretractable sponsons at the bottom of the fuselage and will aerodynamically interfere with inner wing, inboard engine nacelle and the flow on the upswept rear end of the fuselage. The paradropping function is sensitive to the flow passing the rear end. Learning from problems in this area of other projects, one should evaluate the problem with great care.

2.4 Application of a modern Electronic Flight Control System (EFCS)

The future tactical airlifter will have a flight control system which relies on the latest state of the art of "fly by wire" in the Airbus World. This type of flight controls consists of 3 independent hydraulic circuits in combination with mechanical back-up controls provided for rudder and tailplane trim actuator. It includes an envelope protection functions and leads with proven redundancy principles to a high reliability and safety standard.

For FTA application, the system may be simplified and must be capable to be flown with reduced envelope protection also.

In order to save weight and reduce vulnerability, the electrical back-up hydraulic actuator (EBHA) principle could be applied. This system allows flight using electrical power in event of all hydraulic circuit loss, thus avoiding the need for a third hydraulic circuit but still meeting the safety objectives. The EBHA operates with a closed-loop hydraulic system powered by an electrically driven pump integrated in the actuator. The possible deletion on one hydraulic system may more than compensate for the additional weight and complexity of the EBHA.

This promising concept should therefore be studied further on. Following successful testing on an A320 prototype, more work is necessary to achieve an industrial standard mature for application on FTA.

The flight control system will be operated via side stick. This will be the first time in a military transport aircraft and the according cockpit architecture has to be developed and verified. Pilots familiarisation and acceptance must be achieved.

Development simulators with full simulation of flight mechanics and flight control system characteristics (flight control laws incl. envelope protections) have to be established.

2.5 Autonomous and silent high Precision Navigation and Landing

From the analysis of FTA missions and expected threat, the following precision navigation application areas can be defined:

- capability for low level flight at night and during adverse weather without detectable sensors (silent terrain following);
- reduced probability of detection and threat (terrain avoidance/threat avoidance);

- capability to land on non-instrumented fields.

All these functions require extreme accuracy and reliability.

Low level flight on the basis of terrain referenced navigation (TRN) - digital terrain data base is available for wide ranges of the global surface - can be a solution of the problem. This system has been successfully tested on fighter a/c like Tornado already. For application in a transport aircraft, however feasibility and effectiveness still must be proven. Another requirement is distortion-free navigation. The solution is a close functional integration of at least 3 independent navigation sensors (TRN, GPS and IN). Intelligent combination and filtering allows failure management, system moding and leads to a high system integrity. This will provide the required highly accurate and reliable output (see Fig. 5). This system is currently under investigation with the designation RAPIN (Reliable Autonomous Precision Integrated Navigation) and when mature will offer a wide application area for future military operation.

Board-autonomous landing capability without ground-based support by radio navigational aids and without standard approach procedures requires in addition to a self-contained high precision navigation system an energy management function, which determines the required configuration changes of the aircraft along any given flight trajectory.

Autonomous landing under night and bad weather condition needs vision enhancement. Besides radar or IR-imaging, a synthetic sight on the basis of the digital terrain data could be generated. Again, here a very precise navigation is required to establish at all times the position on the flight path from which an artificial perspective view (view inside out) into the terrain relief can be computed. This artificial vision can be overlaid with the natural vision, e.g. combined in a head up display. Systems like this are under development in various companies/nations just now and the technology is expected to be mature when the development of the future mil. transport will commence.

	Nominal Perform.	Performance under Conditions of				Related to Ground	Operational Area
		Rough Terrain	Smooth Terrain	Water	Jamming		
IN	1 nm/h	Good	Good	Good	Good	No	Total Coverage
TRN + IN	50 m	Good	Medium	Poor	Good	Yes	Total Coverage
GPS + IN	25 m	Limited by Screening	Good	Good	Medium to Poor	No	Total Coverage
IN + TRN + GPS	25 m	Good	Good	Good	Good	Yes	Total Coverage
Integrated Nav	<25 m	Good	Good	Good	Good	Yes	Total Coverage

Fig. 5: Navigation System Performance

Rotorcraft 2020

Bruce B. Blake and Dr. Mark B. Tischler

Summary

Rotorcraft have played a key role in all recent conflicts, as witnessed by use of AH-64's in the opening days of the Gulf War to neutralize Iraqi border defense, and the continuing rotorcraft role in regional conflicts including Somalia, Iraq and Bosnia. Emerging rotorcraft systems coming on-line in the NATO countries during the coming decade include the Comanche, Tiger, NH-90, EH101, and V-22. These systems will exhibit improved capabilities in weapons integration, all-weather operations, and will have increased performance and agility. Future systems envisioned for the 2020 timeframe will make full use of active control technology and smart structures to reduce noise and vibration and increase agility in a care-free manoeuvring vehicle. Advances in avionics and GPS technology will be integrated in an advanced glass cockpit that allows for increasingly accurate navigation and weapons delivery in all weather conditions with a tolerable pilot workload. Increased use of integrated modular avionics architecture will improve mission reliability, facilitate maintenance and improve supportability. Further, the full use of unmanned air vehicle (UAV) technologies in a combined manned-unmanned force structure will dramatically improve mission effectiveness without exposing the pilots to unnecessary risks in hostile territory. This paper explores the vision for future rotorcraft technologies as an important component of AGARD Aerospace 2020.

Operational Missions

Rotorcraft are vehicles which excel in missions which require extended efficient hover and low speed omnidirectional flight as well as forward flight at the highest possible speed. Configurations include helicopters where the rotor provides both lift and propulsion in forward flight and tiltwings or tiltrotors where the lift is carried by the wing in forward flight. The use of direct thrust and/or wings to offload the main rotor is likely to become more common to enhance the performance of more conventional helicopter configurations.

Typical battlefield missions are and will continue to be armed scout/attack, utility and troop cargo transport. Principal maritime missions will continue to be anti-submarine anti-surface vessel, search and rescue and utility. More specialized missions, such as special operational forces and airborne early warning, will be performed by specially equipped versions of the basic vehicles since the number required usually do not justify development of a totally new aircraft. Cost savings from commonality is a powerful reason to develop and operate the fewest number of basic vehicles.

Application of emerging technologies should make possible new missions where unmanned rotorcraft will have a significant role. Surveillance and attack in high threat environments are examples. Since unmanned vehicles have great design freedom from a size, equipment, and signature viewpoint, several new vehicles suitable for a variety of roles should be feasible.

Key Technologies

Computing Power

Assuming that recent history is a good indicator, the speed at which computing hardware and software develops is orders of magnitude faster than any other technology which will influence rotorcraft capability by 2020. Twenty five years ago successful moon landings were accomplished with a computer having about 8 K memory, and fairly simple software. Today a gigabyte of memory comes with a home computer, and on board mission software exceeds two million lines of code. Current estimates are that one desktop computer in 2020 will be as powerful as all the computers in Silicon Valley today. By harnessing this much capability properly, major improvements in both the development process and in vehicle performance can be realized.

Integrated Product and Process Development will allow designs to be better optimized through linkage of analytical tools, automated design and tooling methods, as well as factory production flow simulations. The result will be a more sophisticated approach for addressing weight, cost, producibility and performance issues.

By 2020 advances in processing power will lead to extensive application of integrated modular avionics architecture for the core avionics system. Helicopters with such systems should be more adaptable and more easily upgraded and should benefit from enhanced mission reliability, better avionics system battle damage tolerance, improved maintainability and reduced costs through reduced spares holdings. Use of this anticipated increase in onboard computing power will continue to present a major challenge in controlling the development and verification costs of very complex mission critical software.

Vehicle Aeromechanics

Both the helicopter and tiltrotor blades operate in a complex environment and represent a multiparameter compromise among aerodynamics, structures, vibrations and acoustics.

The best hover performance is obtained with a specific set of blade planform, twist, and airfoils.

For helicopters in trimmed forward flight, the disc is edgewise so that the advancing blade operates a high subsonic Mach number and low angles of attack, while on the retreating side it is nearing stall. Blade airfoil and thickness distribution, planform and twist must be carefully optimized to ensure efficient performance around the rotor azimuth throughout the flight envelope. The forward flight environment is illustrated in the accompanying figure.

From a structural viewpoint each blade has inplane, out of plane and torsional bending modes whose frequencies can be in the range of rotor harmonic excitation. Stiffness and mass distributions must be adjusted to make certain no natural frequency is close to a significant harmonic of rotational speed so as to avoid severe vibratory stress and hub load amplification. Other phenomena, such as intersection with the trailing vortices from other blades, the influence of airframe structural modes, and transient effects of agile maneuvering further complicate the problem.

For a tiltrotor or tiltwing aircraft, the prop rotor must operate at very high thrust in hover, and at very low thrust in cruise where the forward propulsive force needed may be less than 10% of the hover thrust. Rotor interaction with the wing flow-field also can cause large force changes on the blade over a very small range of rotor azimuth.

Rotor System Design

The status of current technology is that most of these phenomena are conceptually understood. The most advanced analyses match wind tunnel and flight trends reasonably well. Consistent reliable pretest predictions of detailed rotor parameters and of overall aircraft response has yet to be achieved. Design is carried out using prior experience, guided by available analysis and wind tunnel test results. "Modify as necessary" in flight test completes the process.

Optimization techniques which allow rapid parameter searches for a total aerodynamic and structural design which meets specified requirements, do not currently exist for helicopter design problems. Research on possible approaches such as adapting methods used for fixed wing optimization to the more complex rotorcraft problem are being carried out. Use of robust optimization methods should ultimately allow much quicker design of blades and other airframe components with minimum flight test modification.

The process of developing a control system using vibration, stress or aerodynamic load sensing to actively modify the shape of the blade in a practical operational design lies in the future, but can be achieved. New work being carried out in the application of smart structure materials to rotor blades holds promise of major improvements in performance, vibration and noise. Previous experience with complex mechanical blade control devices indicate that up to 90% vibration reduction and 10 to 20 db noise reduction may be possible although these have not been achieved at the same time.

The smart structure approach utilizes piezoelectric or other similar materials which have the ability to expand and contract in response to low power electrical signals. By embedding this material in a rotor blade, it is possible to vary the blade twist, or camber or to deflect trailing edge flaps. Since this can be accomplished at very high frequency, the key blade parameters can be varied around the azimuth as desired for any flight condition. This technology is currently in the laboratory and small scale model test phase. Considerable additional research, testing and development will be necessary to bring it into operational service. Some experiments also indicate that it may ultimately be possible to control the rotor using smart materials rather than the mechanical swashplates and pitch change mechanism currently used. However, achieving bandwidth, stroke and power will require extended development.

Powerplant

Both the helicopter and tiltrotor aircraft operate primarily at low altitudes and cannot capitalize on the improved engine efficiency of operating at high altitude. Recent experience revealed an operational need for increased payload and range and reemphasized the need for efficient erosion protection systems and lower signatures. The primary technologies which will provide these increases are those which lead to improvements in engine specific fuel consumption and power-to-weight ratio.

Crew Workload

The most demanding rotorcraft missions are carried out very close to the ground at night or in bad weather and under combat conditions. The crew is expected to fly, navigate, communicate, avoid threats, and carry out the support or combat mission. There are several developments underway or planned which should help reduce crew demands to a manageable level.

Current efforts on the Handling Qualities Requirements of mission capable rotorcraft have developed extensive criteria on desirable stability and control characteristics and the relationships between these criteria and the pilots visual cue level. By 2020 these concepts will be fully embodied in operational aircraft resulting in lower loss rates.

Research emphasis on the use of advanced enhanced and synthetic vision systems and the methods of fusing sensor data into clear and unambiguous representations will lead to visual flight capability effectiveness in extremely degraded visual environments.

By 2020 it is expected that digital map of the world to 1 meter resolution will be available on board any aircraft, and that it will be periodically updated from satellite survey. Second or third generation GPS should show aircraft location to comparable accuracy. Details of nearby obstacles and cultural features will be obtained from image fusion of passive sensors using pixel flow techniques, and active high resolution sensors such as laser or millimeter wave radar to see fine details such as wires and branches. Combining the high resolution map and the fused sensor information on nearby features as inputs to appropriate control laws will make possible hands off nap of the earth (NOE) flight whenever desired.

By 2020 full advantage will be taken of fly by wire (FBW) and fly by light (FBL) flight control systems. Redundant FBW/FBL systems offer enhanced survivability and maintainability.

Battlefield operations require clear communications among the various force elements to carry out coordinated battle management strategy. Reliable data reception and transmission will require a major improvement in antenna design relative to any current aircraft. Development of phased array multiple wavelength antennas and use of satellites for non line of sight communication are possible approaches. The unique rotorcraft operating environment very close to the ground, and necessary compatibility with low observable designs make this very challenging.

Processing the data available from onboard sensors and obtained from other battle team members will follow from major upgrades to the first generation Pilots Associate systems which should become operational in the 2005 to 2010 time frame. The massive amount of data available must be digested and prioritized to allow the aircrew to make effective decisions in times of stress, fatigue and haste.

Structural Diagnostics

Rotorcraft are unique in that they depend on the structural integrity of many nonredundant fatigue loaded components for safe operation. These include the rotor hub, blades, drive system and control system components.

Most current rotorcraft use conservative maintenance, inspection and part retirement lives based on development testing, anticipated use and overall fleet service experience. It is possible for a few vehicles to be subjected to unusually severe use, or to experience an unexpected maneuver beyond test data. In this case the normal component maintenance or replacement interval may be too long. For most aircraft in normal use the conservative schedule will dictate unnecessary maintenance activity and the replacement of good parts having a great amount of life remaining.

Health and Usage Monitoring Systems (HUMS) aimed largely at monitoring drive system components are now being widely adopted to reduce maintenance costs and to significantly improve safety. These systems use information from a range of sensors to allow continuous automatic fatigue life tracking of critical components so that individual components can be inspected/replaced based on actual rather than predicted usage. HUMS also monitors parameters in order to detect the onset of component failures long before the damage becomes critical. For example, a crack in a transmission gear does not generate debris and therefore does not activate a chip detector. However, monitoring the transmission vibration and acoustic signatures using suitable pattern recognition techniques can detect growth of small cracks which can be identified by maintenance crews for remedial action long before the crack progresses to component failure.

By 2020, full capability HUMS covering all critical components should be standard equipment on all inservice rotorcraft.

Detection

Rotorcraft signature suppression technology differs significantly from fixed wing aircraft. Operating in ground clutter with both static and dynamic signatures presents both opportunities and problems.

Acoustic detection is dominated by low frequency harmonic components of main and tail rotor noise, and can be very azimuth sensitive. Use of smart structures and other techniques discussed in the Aeromechanics section, to modify blade vortex interactions should be capable of reducing radiated noise by 10 to 20 db.

Radar signature has both a static component from the airframe similar to other vehicles, and a dynamic or doppler component due to rotating blades. Careful attention to shape, external smoothness and use of absorbent materials can significantly reduce signatures when compared to current aircraft.

Optimizing a design is an extremely complex process which must account for ground clutter, detailed threat characteristics, and various battle scenarios as well as an accurate model of vehicle characteristics. This is best accomplished through repetitive use of constructive simulations to achieve a design having the best survival probability. Anticipated future use of Distributed Interactive Simulation is an essential part of this process.

Infrared signature is dominated by engine and exhaust temperature as with other vehicles. The most effective IR reduction method is to design the aircraft initially to incorporate shielding, exhaust dilution, etc., rather than adding large external devices as an afterthought to an existing aircraft.

Summary: Rotorcraft 2020 Capability

1) Helicopters will have operational speeds of up to 200 kts. Addition of wings and/or direct thrust will increase maximum speed and agility in high speed flight. Tilting rotor and wing vehicles will be capable of 400 to 450 kts.

2) Mission radius will be at least 50% greater than today.

3) Vibration and noise levels in occupied areas will be comparable to today's modern jet transports.

4) Structural integrity of all critical components will be continuously monitored. The pilot will be warned of potential failure with ample time to take corrective action or to land. All maintenance requirements will be displayed to crew chief at landing. Maintenance man-hours per flight hour will be less than half of current generation rotorcraft. Components will be replaced as required rather than on a predetermined schedule.

5) A cockpit having internal displays of quality sufficient for nap of the earth (NOE) flight will be practical for missions in zero visibility or in battlefields with high energy laser threats which require window blockers.

6) Hands off, all weather, NOE flight and navigation will be an option available to the pilot, either for attack aircraft or for cargo aircraft with external Sling load.

7) The pilot will have available an easy to understand real time display showing a "God's eye" view of the battlefield with threats, friendlies, and recommended strategy options.

8) The pilot will be able, when desired, to prefly a mission in the cockpit using up to date information to explore various mission profiles.

9) Battlefield detection by enemy threats will be much more difficult than for current aircraft even as threats become more capable.

Reconfigurable Flight Control at Wright Laboratory

P.R. Chandler

Introduction

Various government departments, including USAF Wright Laboratory, Naval Air Development Center, NASA, and ARPA are sponsoring the development of reconfigurable flight control systems. The reconfigurable system detects and compensates for in-flight failures and damage to maximize handling qualities and performance. Considerable success has been achieved to date. Some concepts have had limited flight tests, numerous piloted simulations have been performed on a range of aircraft, and lower risk portions of the technology have been transitioned to production A/C.

The full benefit of reconfigurable flight control is just now being uncovered. Reconfigurable control is a subset of nonlinear or adaptive control. Compensating for large discrete events pays handsome benefits in survivability, fault tolerance, and safety of flight. Expansion of limited reconfiguration to a more fully adaptive approach pays even greater dividends. Such an approach will lead to faster development, reduced development costs, significantly less simulator tuning, a high degree of robustness to modeling errors and changes, and easy extensibility to new configurations and models. The technologies key to achieving these benefits are real-time parameter IDentification (ID), on-line control design, control allocation, and command limiting. Work to date has concentrated on Failure Detection, Isolation, and estimation (FDIE), and control power redistribution. These techniques generally involve extensive off-line development and are heavily model dependent. Due to the effort involved, the reconfiguration capability is limited. A full ID and on-line design approach is highly adaptive. However, the technology is not yet available to field a fully adaptive flight control system today with acceptable risk. In particular, the ID must be fast and accurate, identifying critical control and stability derivatives. The on-line control design must be highly nonlinear and accommodate a full range of hard limits, as well as be computable on-line. In addition, stability and robustness analysis of an adaptive system must be made to ensure the system can be flight certified.

In the following sections, only the efforts sponsored at WL will be discussed.

Background

One of the earliest studies for WL by Grumman in '78 entitled "Dispersed and Reconfigurable" [1] identified a significant improvement in survivability for Vietnam era fighters, if the control laws could be reconfigured after battle damage. Significant strides were made to develop the reconfigurable algorithms under the WL 6.3 program "Self Repairing Flight Control Systems" (SRFCS) in the mid to late eighties [2]. There were two efforts in this program; the SRFCS F-15 Flight Test, and the Control Reconfigurable Combat Aircraft (CRCA) simulation. Both efforts used algorithms based on a bank of failure detection filters with discrete gain sets switched in after failure/damage detection.

The reconfigurable F-15 flight test [3,4] program was performed by McDonnell Douglas, General Electric (Binghamton), and Alphatech. The F-15 Flight Test (flown at NASA-Dryden) emulated a horizontal tail missing scenario in flight. Surface floating and locked at deflection failure modes were also flight tested. The locked at deflection failure was the most severe. Without reconfiguration, the pilot had great difficulty in canceling the cross-coupled moments. With reconfiguration, the pilot could not tell that there was any cross-coupling (but there was a reduction in the available pitch and roll rates, as expected). The F-15 flight test performed well, but extensive adjustments were needed during flight test.

The CRCA development program was performed by Grumman, Lear Astronics, Charles River Analytics, and personnel at WL [5,6]. The CRCA effort developed algorithms somewhat similar to the F-15 flight test algorithms, and applied them to an advanced (paper) air to air fighter. In the CRCA effort, the concept of model based estimation for event driven Fault Detection and Isolation (FDI) was employed. A bank of Kalman filters was run in parallel, and a "predetermined" discrete set of failure hypotheses were tested using the recorded return difference (the difference between a no fail filter estimated output and the sensor output). Only control derivative changes were hypothesized. Also, a model of the healthy unimpaired aircraft was required (the no fail filter). Modeling error was induced by maneuvering flight, hence, thresholding was needed. The fundamental problems of false alarms and missed detection are inherent in this approach, therefore three consecutive return differences were evaluated by the fault detection algorithm. After a failure was detected, the control derivatives were estimated and the control effort was reapportioned so as to minimize the Euclidean norm of the applied control effort shortfall.

An architecture study was also performed by Grumman. This study showed that the reconfiguration algorithms, by providing a degree of functional redundancy, could allow the flight control architecture to be simplified, thereby reducing weight

and cost. In particular, primarily simplex actuators and a dual hydraulic system could be used with no impact on safety of flight. In summary, the algorithms, while successful in their limited application, needed continued development.

An investigation into a follow-on to the SRFCS program was started in the early '90s that could lead to a full envelope flight test program of reconfigurable control. This culminated in a study effort by Northrop Grumman entitled "Adaptive Multi-Dimensional Integrated Control System" to identify the most promising technologies for continued development [7]. The recommended technologies include; reconfigurable flight control, distributed miniature sensors for accelerations and strain, active flutter suppression, system identification for both rigid and flexible modes, specialized neural networks hardware, and maneuver load control. This effort was completed in CY95. Some of these technologies are being addressed in on-going and future programs (see Future section).

Current and Recently Completed Efforts

In the early '90s, the next, or 2nd generation of reconfiguration algorithms was developed under SBIR and 6.1 efforts to address the earlier identified limitations. Continuous system identification is used, rather than event FDI, and the control laws are designed on-line, rather than using a fixed set of gains that are switched in. These algorithms are more fully adaptive and do not suffer the limitations of the earlier algorithms. These efforts include the Neural Net Flight Control System (NNFCS), the Self Designing Controller (SDC) [9], and WL 6.1 in-house efforts [10,11] under the "Multivariable Flight Control" task. The first two are SBIR efforts with Barron Associates. All three of the efforts use a receding horizon control approach which calculates the required control inputs for a fixed horizon. This approach puts considerable lead into the system, yielding good tracking without excessive control activity. The NNFCS, primarily designed for high alpha, was demonstrated in a F-16 piloted simulation at Lockheed. The system performed very well with virtually no tuning required in the piloted simulation. What little tuning there was involved simple changes to the handling qualities models.

The Self Designing Controller expanded on the NNFCS effort. The NNFCS receding horizon controller requires a model of the aerodynamic forces and moments on the aircraft. This is done by using a neural net to model the forces and moments in a ground based simulation [8]. The network is then interrogated in flight. The SDC, in contrast, continuously identifies stability and control derivatives in real-time on-line. A recursive least squares approach is used which penalizes changes in the derivatives to significantly improve the estimates. Also, the SDC emphasizes reconfiguration for failures and damage, which the NNFCS does not [9]. To date, these algorithms have performed very well in simulation on a variety of failure and damage scenarios. The SDC adaptive algorithms were demonstrated in the Spring of '96 on the VISTA F-16 in-flight simulator. The flight test culminated in the landing of VISTA with a missing left horizontal tail (emulated) under full adaptive control. This is a major milestone and the first flight test of continuous in-flight system identification and on-line control law design to land with major damage.

The development of the reconfiguration algorithms is continuing under the WL in-house 6.1 effort. In particular, the static least squares approach is expanded to include relationships between the derivatives derived from flight mechanics. These relationships radically improve the quality of the estimates [10]. The receding horizon controller is discrete in formulation, as opposed to the NNFCS, which is continuous. The discrete form more readily accepts actuator hard saturation limits. These limits significantly degrade the tracking ability of the controller, if not accounted for. For the open loop unstable F-16, rate saturation could lead to departure. These limits are accounted for in the design through a simplified form of linear programming [11]. A feasible pilot input is determined that does not result in saturation in the prediction window. This has yielded excellent tracking in non-real-time simulation.

Recently Started Efforts

More work needs to be done to transition a fully adaptive flight control system to a production aircraft. The Reconfigurable System for Tailless Fighter Aircraft (RESTORE) program is the further development and refinement of the adaptive control methodology. The objective of the RESTORE program is to develop reconfigurable control law design methods and algorithms and apply them to an advanced low signature (tailless) fighter configuration. The long term objective of the technology is a control approach that is highly automated, highly adaptive, and easily transported to other platforms. This will significantly reduce the time, cost, and risk of developing flight control laws for new aircraft or updating the control laws for aerodynamic or configuration changes. If the handling qualities are found to have deficiencies during flight test, this can be easier addressed by simple changes to the handling qualities models, rather than extensive iterative redesign and test. The SDC and other related efforts have only addressed part of the needed full on-line control design methodology.

A fully adaptive methodology must also accommodate the complete design process, which

includes actuator saturation, control allocation among surfaces, control axis prioritization, multiple unstable axes, command limiting, flexibility coupling, and load alleviation, as well as the continuous on-line optimization of various performance factors, such as drag or signature. The objective of RESTORE is also to apply the methodology to the highly challenging aircraft configurations of the future, rather than the classical three surface (aileron, rudder, elevator) aircraft (F-15,F-16). These future aircraft have multiple nontraditional surfaces, are highly coupled, highly nonlinear, unstable in multiple axes, and are severely limited in available control (particularly yaw) due to signature constraints. RESTORE becomes an enabling technology for these aircraft configurations by fully exploiting the available control power under all flight conditions to maximize performance and survivability.

The resultant products of the RESTORE effort are a set of algorithms for the on-line automatic design of control laws. The algorithms include: a) system identification to account for damage and modeling error; b) control laws that meet handling qualities and tracking requirements; c) constrained optimization to account for actuator saturation, load limits, etc.; and d) control allocation over a suite of effectors to minimize surface activity, drag, signature, etc. The RESTORE contracted effort started in Sep. CY96 with a dual award to Lockheed Martin Tactical Aircraft Systems and McDonnell Douglas Aircraft. By Sep. CY99, the contractor will develop the algorithms as outlined above, select a representative low signature (tailless) fighter configuration, apply the algorithms to this configuration, and demonstrate the capability in a piloted simulation at the contractors facility.

Future Efforts

Possible follow-on efforts include contributing to the FI FATE effort by applying the RESTORE control algorithms to a flight test of a tailless UAV. UAV's are an excellent application for reconfigurable control. Because of the emphasis on cost for UAV's, the highly automated on-line control design approach would lower the control system development cost as well as the life cycle cost from control updates. In addition, the certification procedures for an adaptive control system for an unmanned aircraft could be significantly less than for a manned aircraft, further lowering cost.

If highly agile UAV's are required, then the reconfigurable control design needs to be expanded to very high g's (20-30) and/or very nonlinear dynamics (post-stall). This capability possibly could be accomplished by refinements of algorithms that are presently being developed.

One functionality being planned is on-line learning. The on-going reconfiguration algorithm development is adaptive in nature, meaning present performance is optimized from a locally identified model. A learning system, in contrast, will retain this information (model or control) by updating a global model (or controller) through spatially localized learning. If the aircraft should reenter the state at a later time, at which the previous adaptation occurred, the learned response can be used, rather than readapting. This is useful if: the a priori model has appreciable modeling errors due to uncertainty; the specific vehicle is different from the generic vehicle; there are slow changes to the vehicle due to wear or stress; and or course for failures and damage for the remainder of the flight, which are then repaired.

Neural networks are a good candidate for learning since they are a very powerful modeling tool and have an efficient on-line representation. Neural nets are generally too slow for adaptation, but, by running in background mode, could readily update the global model locally. Neural nets could also be used to represent an inverse model of the aircraft. Thereby mechanizing a form of dynamic inversion or plant cancellation.

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The International Test And Training "Range"

C. Van Norman

Abstract

This paper describes the test range of the year 2020 and its anticipated capabilities. It also describes technological and organization changes that are key to realizing this envisioned future test range.

Introduction

Changes in the international geopolitical and military technology environment are forcing changes in the way weapon systems are acquired and integrated into the NATO force structure. Dealing with these changes is a challenge to the international test and evaluation community. The international test and training range envisioned in the year 2020 will have a key role in meeting this challenge. While the armament industries of the world are expected to be significantly reduced from their peaks of the cold war, there will be no dearth of new weapons systems concepts or proposed enhancements to existing systems. With the movement toward software intensive, highly integrated weapon systems, the potential system configuration combinations will increase, posing complex test and evaluation challenges. Multi-national corporate expansion and the extension of business relationships across what had been cold war barriers further complicate the choices for the NATO planners. An example of both the power of software and international linkages is seen in recent news articles regarding the Boeing 777 wide body aircraft. It is described as being completely designed by computer, with its four million parts coming from 542 suppliers in 42 countries. In addition, proliferation of military technology, including weapons of mass destruction, will continue to pose significant risks to peace.

Thus the NATO planners are faced with a composite of the problem facing many national military authorities: A more diverse threat, a need for a more responsive set of forces that can be scaled to match the threat, selected from a complex set of interrelated weapon system options, in an economic and political environment forcing reduced military spending levels. For NATO, this problem is compounded by the need to integrate forces of countries that may have had significantly different military equipment, command and control, training, and doctrinal legacies. Solving this problem will require both technological and organizational changes.

Technological Changes

Weapon Systems Capability

We can assume that new aircraft weapons systems will be developed in the next 25 years which will employ new technologies. However, we must also assume that many of the aircraft which are in the NATO inventory today will still be viable weapons in the year 2020 as a result of upgrades. By that time, both new and currently existing aircraft will be very capable weapons systems. Although we may not be able to predict exact capabilities, it is safe to assume that they will be software intensive, with millions of lines of onboard software controlling flight and war-fighting capability. They will obtain data from many types of both off-board and on-board sensors and will utilize data fusion to provide battle information to the pilot or system controller. Data on threats, linked from satellites, airborne and ground based sensors and ground forces, will be used to compute the optimal intercept/ingress course. Smart weapons will be employed which utilize data links from the launch aircraft as well as from external sources such as satellites. The current trend toward the use of Unmanned Air Vehicles (UAVs) will continue, driven by fiscal pressures, improvements in avionics technology, and a continued desire to reduce the risk to flight crews. UAVs will assume many roles previously reserved for piloted aircraft.

Use of Modeling and Simulation

The complexity of aircraft weapons systems will require significantly increased use of modeling and simulation (M&S). This M&S will span the entire life cycle of the weapons system and will also provide its linkage to other weapons systems which comprise the larger NATO force structure.

By the year 2020, the test and evaluation process will have undergone significant change and will make unprecedented use of simulated environments. Use of open air test ranges will be more highly focused and flying hours will be significantly reduced. Initial testing will focus on model validation at the system level with determination of the effectiveness of the weapon system in a mission-level scenario as the next step.

As the weapon system matures during developmental tests, the tester will be required to feedback validated model data to update the mission level model. This will result in a parallel test process instead of the serial (developmental then operational testing) test process now in place. More importantly, test results will immediately be translated into military worth and more directly impact the continued development or cancellation of the weapon system.

Testing the complex aircraft weapons systems of the year 2020, will demand a systems approach. It will no longer be enough to verify that subsystems behave as designed. The total system may be

adversely affected by relatively minor interactions between subsystems that may not become evident until system-level testing. Presently, this means that a physical, integrated system is a requirement for system-level testing. In the future, sub-system and system tests may consist of a mixture of physical and modeled components. Currently, availability of physical system components restrict testing and cause test programs to exploit a serial, test article configuration driven approach. But, if subsystem models can be substituted for their physical counterparts, this restriction will be removed allowing greater flexibility in planning and conducting missions.

In addition to system- and mission-level models, other aspects of the system and the test and training infrastructure will benefit from modeling and simulation. Logistic and maintenance models will also be developed and integrated into a composite system model, resulting in a model that can be used to simulate war-fighting capability as well as system availability and reliability.

Models that depict system performance are being used today to predict flight path and minimize fuel and time for test, training, and operational missions. These models validate that the logical sequence of events in mission optimizes fuel economy and minimizes flight time. In addition, automated information systems are currently being used to support mission planning, resource scheduling, and tracking the progress of test projects and crew training. The future will require even more sophisticated and capable systems for automating information-intensive tasks. Developing these systems will stretch software development capabilities for quality and reliability. These future systems will include a much greater use of modeling the critical aspects of flight test missions, training missions, and operational missions.

Range and other environmental models will be developed to interact with system- and mission-level models. These new models and the capability to interact with actual weapon systems via data links will allow flying virtual missions against virtual or simulated enemies. They will provide the necessary environmental inputs to the system and mission models and allow range operators to plan and position key resources to optimize data collection and training. A combination of aircraft models and range facility simulation will also enable actual control rooms to be used to train test conductors and flight test engineers.

System interoperability directly effects mission effectiveness. History is replete with examples of how interoperability problems have cost lives, battles, and wars. For NATO, ensuring interoperability is even more difficult. Individual nations in the alliance have designed their weapon systems to be intraoperable, that is, a country's own systems operate effectively together. But operating with forces from other countries may not have been a major design consideration. In fact, a country's systems may have been specifically designed not to operate with others.

The testing required to ensure that weapon systems developed by various nations are mission effective and can interoperate across military services and within NATO will also necessitate capabilities significantly different from those of today. Because each weapon is designed, built, and tested for one nation's concept on how it will be used in combat, the systems of alliance nations must come physically together to test interoperability. In the future, this physical proximity requirement will be greatly reduced using modeling and simulation.

This increased use of simulated environments will change the purpose of open air test ranges in testing interoperability. The use of physical ranges will be more highly focused as well as significantly reduced. Initial testing will focus on system-level model validation. As the weapon system matures during developmental tests, the tester will be required to take validated system level model data and feed a mission level model. This will result in a parallel test process instead of the serial (developmental then operational testing) test process now in place.

These validated system-level models will then be used in a NATO mission-level scenario to test interoperability. The mission-level modeling will reduce the requirements for open air testing and physical ranges.

Data Communications

Data communications technologies will increase to the point that secure real-time data from almost any source will be able to be economically transmitted to any other point on the face of the earth or to an aircraft in flight. Multiple range control networks will provide multi-sensor data fusion, real time recording, mission control functions, and target acquisition information. Engineers participating in a multi-range test mission will not have to be collocated. A combination of the virtual reality technology and new communication technologies will enable remotely located engineers to work in a "virtual mission control room". Airborne mission control rooms will be utilized to follow aircraft under test over large geographic areas not considered a test range. These aircraft will provide mission control, data processing capabilities, and range safety support. Testing of unmanned air vehicles will be supported with IRIG compliant range safety systems will support on-range missions and long range missions that traverse several test ranges.

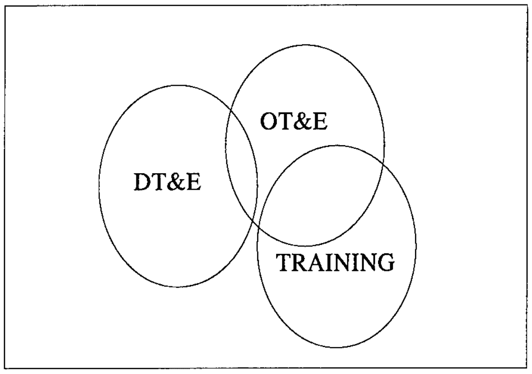

Figure 1: Current Concerns of DT&E, OT&E, and Training

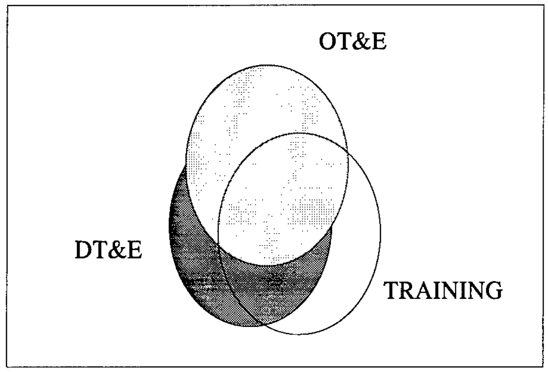

Figure 2: Future Relationship of DT&E, OT&E, and Training

Merging of DT&E, OT&E, and Training

Although not strictly a technology issue, the merging of development test and evaluation (DT&E), operational Test and Evaluation (OT&E) and Training will drive technology requirements. Currently, the scope of concerns for Developmental Test and evaluation (DT&E), operational Test and Evaluation (OT&E) and Training will drive technology requirements. Currently, the scope of concerns for Developmental Test and Evaluation (DT&E), Operational Test and Evaluation (OT&E), and Training are relatively disjoint. DT&E and OT&E have some overlapping concerns and OT&E and training have more in common. The current relationship is depicted in Figure 1.

Forces are driving these three worlds to join. DT&E has been accused of a lack of realism in its processes. To better interject reality into tests, DT&E has incorporated test scenarios and techniques which resemble operational tasks and yet yield the data required to both quantify the system and also determine its readiness for OT&E. The increasing complexity of systems has driven OT&E to obtain more quantitative data in order to understand the test results. Thus, the OT&E community has begun using "DT&E-like" data collection and analysis systems and techniques. Although these changes have resulted in more commonality of purpose, it is doubtful that the worlds of DT&E and OT&E will totally merge in the near future.

Meanwhile, the goals of OT&E and Training are much more common and these two communities have been working cooperatively for years. OT&E's need to test operational suitability is congruent with Training's need to provide effective, efficient air crews. They jointly focus on how to improve the execution of the mission.

There will also be increased synergy between DT&E and Training during the development process. As the weapon system matures through testing, modeling and simulation will be used to develop the techniques required to train the operational air crews. Realistic man-in-the loop simulators will be used very early in the development process to ensure that air crews can be trained on the weapons system.

In addition, future production weapon systems will include the ability to receive and display a variety of up-linked data, including threat data, in the battle environment. This capability can be utilized in peacetime for conducting training in a virtual battlefield. This potential for this capability will underline the requirement for early involvement of the user (OT&E and Training) in the developmental test process. As the system matures so does the training simulator, so that when the weapons system is ready to be fielded, the training and the training techniques will have already been developed.

As DT&E, OT&E, and Training merge further, the separate concerns merge to the extent that it becomes possible to consider a single entity responsible for supporting all three worlds, the consolidated test and training range. Each activity now has enough common requirements so that a consolidated facility for all three activities makes good sense. Even though each world still has its unique needs, the greater commonality will provide cost and time savings, giving the consolidated range an economic advantage over the specialized ranges of today. As we shall see later in the paper, other factors may preclude this consolidated range from becoming a physical, geographical place, but the forces driving this consolidation of test and training make its evolution inevitable.

Reuse as a Technology Leveraging Tool

The development of sub-system-, system-, and mission-level models during DT&E and OT&E presents a golden opportunity to reuse these models during training. Today, the high-fidelity models testers build and use are often discarded after a test phase. But these models, once validated and updated based on flight test data, could help make high-fidelity trainers as well.

Other reuse opportunities include the following:

Common Test and Training Instrumentation Pods

Common hardware and software systems will be shared and available to the ranges to support small programs needing instrumentation, data acquisition, and position determining systems.

Paperless Aircraft Development

Fully integrated systems will support the design conceptualization through the manufacturing and assembly process. This capability enables the creation of digital product models which permits electronic data sharing by everyone involved in product definition. These models will be used to support the design and installation of modifications needed to instrument aircraft and weapon systems.

Test Data Acquisition Systems

Common airborne data acquisition and processing systems will provide the crew and the control room with selected test information. This system will receive commands from the test director to select the parameters to be acquired, the types of processing to be accomplished, and the destination of the processed data. Engineers will be able to focus on different data for different test points. The amount of bandpass required to transmit this information will be very much less than currently needed to send unprocessed raw data. Data acquired during a test point can be stored for later transmission to the ground.

Common data analysis and presentation tools will be available at the engineer's desk. All flight test data will be maintained on-line and accessed via a high speed network.

A common set of analysis tools will be shared across the test community. The data processing and analysis necessary to clear an aircraft to proceed to the next test point will be accomplished in between adjacent test points. This will help reduce the number of missions necessary for a test program by completing more test points per mission.

Custom telemetry systems will be replaced by commercial types of communication for information exchange between the aircraft and the ground. Control rooms and simulation facilities will share data with the airborne processing system.

Common methods to determine the position, velocity, acceleration, attitude, and altitude rate components will be used on a global scale.

Downsizing/Consolidation

Most NATO countries are currently under great pressure to eliminate all duplication in technical capabilities and consolidate capabilities to the maximum extent possible. There is a prevalent emphasis on high facility utilization and increased customer provided funding. There have been and will continue to be studies to determine the cost savings associated with consolidation of facilities. In most cases these studies show the requirement for a significant up-front investment before life-cycle cost saving can be realized and yet this up-front investment funding is rarely available. Furthermore, political concerns often prevent feasible consolidations from ever taking place. In view of these conflicting requirements, it appears the only solution is to take advantage of improvements in data communications technologies and establish centers-of-expertise as part of a new global shared "range". This solution would make it economically feasible to maintain critical capacities, but, would require organizational changes in order to be practical.

Organizational Changes

The organizational steps to be taken to meet the challenges of the future are equally important as the technological advances. As with the weapon system development, there are more M&S approaches and options than there are funds to exploit them. The projected gains of reusable software, interoperability, portability, distributed operation, scaleability, etc., will only be realized if a cooperative effort to establish standards is maintained and an organizational structure is created to support these functions. Advisory panels and groups, like AGARD will become official standards-developing and approving committees. Participation in these committees and other international standards-making bodies will become a national imperative.

Further, the discipline and effort involved in the verification, validation, and certification process must be increased if the credibility of simulation results is to adequately support major weapon system acquisition decisions. This means that responsibilities for creating and storing information must be clear and that access to that information be responsive to user's needs. Strong configuration control and change management systems will be required to maintain concurrency and fidelity between the models and the systems they represent.

Some local, but costly to maintain, legacy models and information infrastructure systems will need to be phased out in favor of new models designed to meet the architectural and data access standards.

Broad acceptance of standard test and training scenarios will be needed to allow comparative evaluation of the military worth of current and proposed weapon systems or tactics.

Also needed is a way for NATO members to mask classified aspects of their weapon system capabilities, thereby supporting national security interests. Even

though members will be creating system- and mission-level models that accurately demonstrate system capabilities, they will still wish to keep some aspects of system performance secret. An organizational structure that allows interoperability, modeling and simulation, and joint exercises - real and virtual - while still maintaining national security interests will be needed. This may pose the greatest challenge of all.

Summary

All of the preceding discussion validates the need for a common development/test/training environment and points to the difficulties in establishing it. Although it might be desirable to locate all of this activity at a single place, such as concept would be prohibitive from both a fiscal and political standpoint. Thus, virtual integration of multiple, international facilities, laboratories, test ranges, simulated environments will be required to determine the weapons full capabilities for each mission scenario. This international integration must be carried out given the current fiscal and geopolitical environment, while maintaining member nation security interests. <u>The test and training "range" of the year 2020 will be a virtual not a physical place.</u>

Mission Systems Panel

Contents

Information Correlation/Fusion

R. Onken and D. Dewey

1 Definition

Information Correlation/Fusion is the process by which information of varying types and from multiple sources is combined to improve the performance of a given application over that achieved using a single information source. The U.S. DOD Joint Directors of Laboratories (JDL) Data Fusion Subpanel (DFS) has developed a model of data fusion that identifies four levels of fusion processing products. The four levels are:

Level 1 - Object Refinement, which includes data alignment, association, tracking and identification of individual targets;

Level 2 - Situation Awareness, which includes the processing that creates an assessment of the current situation based on the relationship between the various targets processed in Level 1;

Level 3 - Threat Assessment, which projects the current situation into the future to draw inferences about threats and opportunities;

Level 4 - Process Refinement, which provides resource management for such activities as the prioritizing and tasking of sensors.

2 Why Use Information Correlation/Fusion

As battle space complexity, threat lethality, and threat maneuverability increase, there is an increasing need for faster defensive reaction time and for much improved awareness of the battle situation. Information correlation and fusion is an emerging technology that offers a cost-effective means of meeting these needs by improving target detection range, target tracking performance, target identification capability, situation awareness, and threat assessment, and reducing pilot or operator workload, payload weight, and cost.

3 Application of Information Correlation/Fusion to Unmanned Tactical Aircraft (UTA)

There are two major applications of Information Correlation/Fusion for UTA's. They are Autonomous/Machine Decision Making and Off-board Decision Making/Reporting.

3.1 Autonomous/Machine Decision Making

In this application, a computer must perform a role currently filled by a human being. Therefore, the computer program must be capable of sifting through many separate streams of information fusion process. A major question to be answered is where in this process should the data be fused. If the data is highly correlated, the cost of moving it around on the aircraft can be greatly reduced if it is fused near its origin (e.g., the sensor). However, this kind of fusion must not interfere with subsequent processing of the data by making it, for example, impossible for an Autonomous Target Recognizer (ATR) processor to function correctly. Data streams which are highly uncorrelated are most effectively fused near the end of the decision making process. An example of this might be the fusion of platform position information (GPS coordinates & altimeter readings) with target detection decisions from the ATR. This particular fusion is best done in the last stage to compute a targeting solution for the weapon.

Some of the information streams which must be fused in UTA applications will be generated from archival storage. Any mission planning data downloaded to the aircraft prior to takeoff falls into this category, including the templates used for target recognition and navigational waypoint updates. To allow for rapid retargeting, some mission planning data should be updated in flight via high-speed RF data links.

There are two major limitations in the technology which must be overcome prior to fielding operational UTAs. First and foremost, ATR algorithms are still not sufficiently reliable despite many years of significant research effort. The problems primarily stem from a lack of robustness; if the algorithm was not trained on the precise target (i.e., one with the same orientation and aspect ratio) imaged during the mission, it will likely fail to detect the target. It is possible that neural networks may overcome this limitation. The second limitation is in the actual fusion of the information being generated by multiple sensors. So far, much of the work in this area has been ad hoc. Situations in which rigorous analysis has been performed tend to be very specialized (e.g., the fusion of one 3-5 micron image with one 8-12 micron image for the purpose of noise removal). What is missing is a general theoretically framework which specifies how sensor fusion should be performed in a wide variety of specific applications.

If the rapid increases in computing power continue as they have until 2020, a laptop computer will have more processing power than a currently operational Cray processor. This opens up many possibilities. First, many brute force solutions to the problem of ATR, which are considered to be impractical today,

will become feasible. For example, an ATR system that uses a pattern template to match over all possible targets at all possible scales, orientations, and positions in the image, may be a cost effective solution. Many elegant ATR algorithms will also become practical with such increases in computing power. Increases in processing power will clearly also make sensor fusion more practical. For example, it will be far cheaper to embed very powerful processors in the sensors for the purposes of image fusing and/or compression. Since communications bandwidths onboard the aircraft are likely to be limited, processing power can be used to overcome this deficiency.

Onboard communications channels for UTAs in 2020 will need to be very fast indeed. Undoubtedly fiber optic technology will be used as the transmission medium. However, the network capacities envisioned will probably not be fast enough to fully exploit the information correlation/fusion technologies for UTA's.

3.2 Off-board Decision Making/Reporting

The implementation of Off-board Decision Making/Reporting is currently limited by the lack of high-speed (e.g., wide bandwidth) communications channels. Unfortunately, the communications spectrum is a limited resource; it cannot be created, only reallocated. Through the use of compression technology, however, it is possible to substitute computational capacity (which is constantly increasing) for limited communications capacity. Thus, as processor performance increases, so too will communications bandwidth. This is especially the case in the area of video compression, where a sequence of images contains large amounts of both spatial and temporal redundancy which can be removed before transmission in order to boost the effective throughput capacity of the channel. Also, the human eye is unable to detect many types of distortion in a video sequence (blurred images in areas of rapid motion), and this fact can be used to further reduce the throughput requirements of the channel.

The current state of the art in this area is embodied in standards, including MPEG (motion picture experts group) I & II and H.261/H.263 for video teleconference. The MPEG standards are designed to be perceptually lossless and to operate at relatively high bit rats (between 1.5 and 20 Mbits/second). The teleconferencing standards, on the other hand, can operate at very low bit rates (28 kbits/second and up), but they do introduce noticeable distortion into the video sequence. For UTA applications, both groups of algorithms currently suffer from two serious problems: high complexity encoders and high data latencies. Work is currently being done on many fronts to overcome these limitations, including the use of wavelet-based image and video compression.

Unfortunately, the amount of communications capacity available for off-board decision making and reporting will be very limited in the year 2020. In fact, as cellular telephone, wireless networking, and personal communications services (PCs) become more pervasive, lawmakers are likely to auction off more and more of the military's communications spectrum. This will obviously make the task even more difficult. Countering this trend to some extent is the increase in computational processing power which will make increasingly complex compression algorithms practical. By the year 2020, this processing power should make possible the implementation of compression algorithms which come very close to achieving the Shannon limit (the maximum data throughput possible for a given channel) even when the channel is time varying. Once this limit is achieved, the only remaining solution is to allocate additional bandwidth for the application.

4 Application of Information Correlation/Fusion to Mission Management

Information correlation/fusion plays a role in a number of mission management-related applications including Autonomous Machine Decision Making, Situation Awareness, Command in the Loop, Off-board Decision Making, and Command and Control Links.

For mission management, these applications relate to the ability of the strike leaders on the ground to acquire the information that they need to make decisions. Some of the current technological limitations include real-time processing, high speed communications, and countermeasure susceptibility. As in the UTA case, the major factor limiting communications speed is the lack of frequency bandwidth. In the future, a mission management center must be able to accept large volumes of information from a high variety of sources (strike aircraft, reconn satellites, UAVs, archival data, etc.) and to process this information in a timely manner. Command decisions along with ancillary information (target images or templates, etc) must then be communicated to the strike wings either on the ground (prior to the mission) or in flight. Unlike the UTA case, however, the human elements must be integrated with autonomous and semi-autonomous machine intelligence. This is likely to require many different fusion processes, since a major goal is to present the information to a human operator in a timely and meaningful way.

Increases in computer processing power and a greater understanding of distributed architectures should

make it possible to develop real-time mission management systems that will meet future demands. High speed communications within the mission management center can be carried out by an internal high-speed fiber optic network, and additional networks can easily be added as throughput demands increase. External communications to and from the mission management center will still suffer from a lack of sufficient RF bandwidth, however. Again, compression technologies will be able to ameliorate this problem to a significant degree, but they will not eliminate it.

5 Improvements needed by 2020 in Information Correlation/Fusion for UTA's

For Autonomous Decision Making, major improvements are needed in ATR algorithms, and a better understanding of how (and where) best to perform the information fusion process is needed as well. Both of these are very difficult problems to solve, and progress will likely be slow. Advances in these technologies will likely be evolutionary rather than revolutionary.

For Off-board Targeting/Reporting, however, the prognosis for finding solutions is much better. Great improvements have been made in data compression algorithms in the last ten years, and these have resulted in commercially available products. This area continues to be of major interest to the research community, and the algorithms continue to improve. In addition, the increases in the level of integration of solid state circuits show no signs of slowing, allowing us to conclude that processing power and memory densities will continue to increase. This, combined with the activity in compression algorithms, means that communications systems will likely be operating near their peak bandwidth efficiencies (at the Shannon limit) by 2020. If more communications bandwidth is required at this point, the only recourse will be to increase the frequency allocation available for the application. This is likely to be a problem since bandwidth allocation will be a major problem in the future for the military services well past 2020.

6 Improvements Required by 2020 in Information Correlation/Fusion for Mission Management

Problems with ATR algorithms are less severe in the Mission Management applications since a human is available to assist in the decision-making process. Still, improvements in the algorithms will reduce the requirements for human intervention and will thus speed up the overall process. Much work needs to be done, however, to determine how best to combine information from many sources in the processing. Current mission planning systems basically use a different subsystem to process each type of information, relying on the manual labor of human beings to put the pieces together. These Mission Management systems are not capable of real-time mission management, where new target strikes can be made after the aircraft have left the ground and is in a current mission.

The communications requirements for Command in the Loop, Off-board Decision Making, and Attack Coordination required for the mission management center are similar to those required for the UTA. In both cases, large amounts of communications bandwidth will be needed, and advances in compression and computing technology will likely help greatly in making the applications feasible. As before, these advances alone will not be enough to satisfy the demand for bandwidth; ultimately, either more RF spectrum will be needed or the expectations of the user community will have to be scaled back.

7 Other Supporting Technologies Needed by 2020

7.1 Automatic Registration and Alignment of Data For Multiple Sensors

In order to successfully fuse data from multiple sensors, the data must be in a common spatio-temporal frame or reference. This is an issue both for fusing data from multiple sensors on the same platform and for fusing data from multiple platforms. In the case of a single aircraft, dynamic flexure of the airframe, if not properly compensated, can cause serious degradation in performance of fusion algorithms. The multi-platform environment compounds this problem. Registration and alignment for pixel level fusion of imaging sensors is particularly difficult.

7.2 Reusable Software Modules

Current avionics data fusion designs are configured to be custom built for the intended platform. In addition, data fusion designs have tended to use complex, centralized controls. These factors make software reuse difficult. Programs to date have tended to take an ad-hoc, one-of-a-kind development approach, which has driven up development costs. Needed are interface standards to allow interchangeability and reuse of software modules.

7.3 Standards and Metrics

Sensor data fusion is a relatively immature field, and lacks standardized performance metrics relating functional-level performance to mission effectiveness and overall mission objectives. This makes comparison of various fusion algorithms and

approaches difficult and can result in spending substantial resources to develop a fusion product that is of little or no value. Data fusion standards and metrics need to be developed that are meaningful and are widely accepted by government and industry.

7.4 Advanced Multisensor, Multitarget Tracking Algorithms

Implementation of advanced association, correlation, assignment, and tracking algorithms such as multiple hypothesis tracking (MHT) into operational systems offers significant benefits. Advances in computing power and density will enable implementation of improved algorithms that were previously unfeasible.

7.5 Fusion of Data from Disparate Sources

Capability to fuse data from disparate sources is needed. For example, fusion of message data from off-board intelligence sources with onboard sensor data is important.

7.6 Fusion for Higher Levels of Autonomy

As the level of unmanned vehicle autonomy increases, the requirements on the data fusion capabilities also increase. In particular, situation and threat assessment (fusion Levels 2 and 3) sophistication must be increased.

Machine Perception

R. Onken and Dickmanns

I. Machine Perception

Today, Human perception capabilities are still unrivaled by machine capabilities in many aspects, in particular with regard to the pattern recognition performance. Yet, the advances in machine vision, machine recognition and understanding of sound, voice and speech as well as machine perception comparable to other human senses are steadily in progress.

The main drawback at the time being is inadequate computing power available. Computing power, though, is still growing at a great pace for a long time to come.

'GIPS'-class (Giga, i.e. 10 to the power of 9 instructions per second) processing performance is becoming commonplace. This will allow to process high data rates as produced by sensors like imaging sensors in real time. Two color video cameras for bifocal vision require a data rate of the order of magnitude of 30 MB/sec.

However data rate is not the essential point, since it is the information content of an image which is useful for achieving a certain level of the perception performance based on image sequence processing. Within high frequency image sequences there may be a lot of data redundancy, since the situation changes only slowly over time, in general. Therefore, the main task of real-time image sequence processing is to reduce data rates but to keep as much information as possible about the objects to be observed and acted upon.

A uniformly grey image contains as many picture elements (pixels) as a highly structured one; yet the information content of the former may be summarized completely by the symbol 'uniformly grey' and the number coding the grey level. For a 1K*1K pixels image this corresponds to a data reduction of the order of 10 to the power of minus 6.

This is well appreciated in static image processing where segmentation of regions with similar characteristics is a generally accepted first step; region or contour models allow much denser representation and storage of information than handling individual pixels. However, the same has not been true along the temporal axis in most approaches to image sequence processing. Here, for instance, when pursuing the socalled 4D-approach, the combination of both spatial and temporal models of the objects to be observed and the exploitation of continuity conditions along all axes in 3D space and along the time axis brings about the significant increase in processing performance.

In this approach, all processing activities are geared to the next point in time when new measurements are going to be taken. There is no storage of previous measurement data for differentiating or rate computation; this is of special interest in image sequence processing where each measurement means huge amounts of data(10t. The p. of 5 or 6 Bytes), however, very much less new information once the notion of objects and their states have been introduced. The results of previous measurements and evaluations are stored in parameters and state variables of generically defined object models including their dynamic behaviour. In modern control theory, this is well known as recursive estimation which was shown to be numerically very efficient. The flexibility of this approach, for example has been demonstrated in the application of road vehicle guidance, satellite docking, landmark navigation for autonomously guided vehicles, observation of eye and head movements of human operators, and for landing approaches of aircraft. Autonomous landing of aircraft has already been proven feasible by use of machine vision instead of using ground-supported or satellite-based landing aids.

By the year 2020, the performance of machine perception might be close to equivalent to the human's perception and might even surpass the human's capabilities in certain aspects (e.g. 360 ° vigilance, bandwidth). Powerful speaker-independent speech recognition systems with very large vocabulary close to natural language understanding can be expected much earlier. The impressive advances in research of brain physiology and cognition mechanisms are of great support in this field.

Machine perception capabilities can be employed in all kinds of functions in mission performance, which rather should be carried out autonomously, including robots. This capability is the basis for human-like or even more comprehensive situation assessment through the machine. Resulting machine situation awareness can also be used to warrant situation awareness of the humans involved in the mission management and control process. Therefore, machine perception is also of tremendous effect in human-centered automation concepts with respect to autonomous aiding mechanisms for human situation awareness. It is a crucial prerequisite for conscious machines and systems, too (see "Conscious Machines").

Machine perception capabilities will be of great benefit in all levels of integrated mission systems and

subsystems, such as battlefield command and control, precision strike systems and air defense.

II. Conscious Machines

1. On the meaning of consciousness (Sommerhoff, 1990)

In the contemporary scientific literature consciousness tends to be mentioned mainly in a clinical, physiological, or behavioural context to distinguish a state in which the human subject is in full possession of his faculties from a state of sleep or coma. None of these references address themselves to the problem of the nature of consciousness as such. What, for example, is the physiological difference between stimuli to the brain which enter consciousness and the mass of brain-events which never do so?

A systematic scientific study of the phenomenon of consciousness should be allied with the study of perception and knowledge. This points in the first instance to the field of cognitive psychology as the discipline most directly concerned. Yet, we look in vain in the literature of cognition for even an attempt at a systematic scientific treatment of the faculty of consciousness as such. It is symptomatic that in the encyclopaedic OXFORD COMPANION TO THE MIND (ed. Gregor, 1987) the entry on consciousness is written by a philosopher (D:C:Dennett) and not a scientist. Other dictionaries leave us with a case of circularity by defining consciousness by 'awareness' and vica versa. Others are resorted to computer analogies and, for example described consciousness as the brain's „high level operating system". Artificial Intelligence is beginning to give more and more cues while concentrating on the notions of information and information processing, notably on the field of machine perception.

(Sommerhoff, 1990) is adopting the concept of 'internal representations', claiming that the phenomena of human consciousness can be fully accounted for on the assumption that the brain has the power to form certain kinds of internal representations, e.g. representations of the nature of objects perceived in the environment and perceived internally. He is talking about three basic categories of internal representations. One category of these internal representations are the representations of the world and the self-in-the-world, or global world model. These are representations of actualities. In addition, there is another category of representations of possibilities, of merely possible objects, events, or situations. This is the faculty of imagination. Closely allied to this is the faculty of memory recall: the internal representation of past occurrences. One's representations of the present, of the here-and-now, are not representations of a time slice. They cover both the recent past and the more distant past. This may be called the historical dimension of the subjects global world model. The third category of internal representations extends the brain's body-knowledge into a new dimension, forming the basis for introspective self-reports about body functions and associating these to an actual situation like 'I realize that I see a tree' or 'I have a pain when moving my leg' or 'I am just thinking about consciousness'. This is referred to as a second order representation or background representation.

Hence, the following technical definition of consciousness is suggested by (Sommerhoff, 1990): By the faculty of consciousness is to be understood a power of the organism to form internal representations of at least both the first category of actualities and the third category of second-order representations. It follows that nothing can enter consciousness except by way of the brain finding a place for it in its global world model, and that internal representations of ficticious or absent objects, events, or situations enter consciousness only if they are covered by the faculty of second-order self-awareness.

2. Are conscious machines achievable?

Humans are considered as conscious systems in the sense described above. So far, consciousness is only partially developed in machines we know of today. However, the technologies needed for the design of conscious machines are essentially there, somewhat differently mechanizing consciousness compared to biological mechanisms which are not fully understood, yet.

The crucial functionality in order to generate internal representations of the categories 1 through 3 as described above is the function of autonomous situation assessment. Autonomous situation assessment by the machine is achievable in the future by new types of machine senses and machine perception capability (see "Machine Perception"), new types of high capacity and high bandwidth communication links, comprehensive data bases and knowledge bases (dynamic models) of relevant objects concerning the situation.

Regarding a military system, for instance, (e.g. manned or unmanned tactical aircraft, command and control center, etc.), the relevant objects are the military task, the system as such and its components (, including the human operator team) and all objects of the environment which are of relevance. Accessible background knowledge about these objects on which consciousness is based on, includes functional models like calculative dynamic simulation models as well as symbolic models. The calculative model calculates the output of a dynamic process concerned, given an input. The symbolic

model is associated to the simulation model and describes the dynamic process in a way that it can give answers to why this process output came about and what might happen.

This autonomous situation assessment capability may even surpass human capabilities in certain aspects like attentiveness and sensor bandwidth.

The most relevant and promising technology areas for autonomous situation assessment are:

- Computer vision;
- Speech recognition and understanding;
- Multispectral, multitarget data fusion;
- Integrated C2I;
- Data bases for virtual environment;
- Methods for knowledge representation of dynamic objects for virtual environment;
- Methods for problem and conflict modelling for the purpose of situation interpretation;
- Techniques for dealing with data uncertainty;
- Learning techniques.

These technologies are becoming more and more mature (Dennett, 1994; Metzinger, 1995). They need further advancement, though.

Conscious systems can be beneficially employed for all kinds of mission functions humans are involved in. These system are to act in partnership as cooperative teammates. They can be used as subordinate systems or as systems which can act on their own with their own will of survival, for instance. Conscious systems are beneficial as an intelligent cooperative complement in particular with regard to situation assessment and decision making. They represent options for substituting humans in tasks with high risk level or as remote systems.

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Low Cost Inertial Systems

T. Cunningham

Abstract:

The advent of the Global Positioning System (GPS) has changed the rules for inertial navigation to a significant degree. By the year 2020 the role of inertial sensors will be as aiding and backup to satellite navigation derived data. Traditional inertial instruments error budgets will, in many instances, be relaxed by at least two orders of magnitude in non-jamming environments. The commercial market, driven by requirements in the automative electronics area, is expected to provide both accelerometers and gyros at very low cost. Many promising concepts are emerging for low cost inertial components and systems, with accuracy sufficient for a broad spectrum of military applications. These include innovative approaches such as silicon-based Microelectromechanical Systems (MEMS) technology.

The advent of the Global Positioning System (GPS) has changed the rules for inertial navigation to a significant degree. By 2020 the role of inertial sensors will be as aiding and backup to GPS. The performance required for inertial sensors for the NATO missions will depend largely on how reliable, available, and survivable GPS will be in future conflicts.

Pure inertial performance is dominated by the low frequency, or bias, errors of the gyro. This is currently 0.001 deg/hr. or better for ring laser gyros and other sensor concepts. Navigation systems based upon such accuracy meet current mission needs nicely. So do GPS systems, but at greatly reduced cost. Unfortunately, GPS has a number of problems which limit its applicability to aerospace problems, particularly military:

- ◊ It can be jammed.
- ◊ It suffers signal loss and multipath errors that can degrade performance.

Low Cost Solutions

These issues so dominate the design of new navigation systems that many current integrated navigation systems that include GPS systems typically require reversion to pure inertial. Costs of inertial systems suitable for integration with GPS are being reduced significantly by technology advances. Costs of $15k per system can be expected by the year 2000. This is roughly an order of magnitude decrease over systems being built as recently as 1985.

As we look ahead to 2020 we can envision solutions to most of the GPS problems. The next section on High Integrity Global Precision Positioning discusses this. The challenge for inertial systems is therefore to augment and backup highly reliable and available GPS navigation systems. These inertial systems will likely have greatly reduced accuracy requirements to serve important roles:

- ◊ Attitude, particularly yaw axis.
- ◊ Primary navigation for short periods when GPS is jammed.

These requirements are significantly different than today. The dominant error, gyro bias, will be relaxed by at least two orders of magnitude in non-jamming environments.

Automotive Inertial Concepts

Interestingly enough, such low cost systems are currently being built, but not for aerospace applications. The automotive industry is currently creating a significant demand for inertial aided GPS navigators for the cars of tomorrow. The following figure shows the market projection for such systems compared to aerospace demands.

By 2005 the projected demand for inertial systems is very revealing:

- ◊ Aerospace gyro needs <100,000 per year
- ◊ Automotive navigation 500,000 per year
- ◊ Automotive suspension and camcorder stabilization 1,500,000 per year

The most common use of gyros is for automobile suspension systems and camcorder stabilization. Although the accuracy is typically 1 deg/s and far outside the needs for even the lowest accuracy aerospace applications, a typical example based upon a floating mercury core has the following characteristics:

- Very low cost ($1 to $20);
- Good high-rate and high-frequency performance;
- Fluid (Hg) remains stationary as housing (coil) is rotated, causing flux lines to cut through Hg;
- Current flow ("I") is proportional to angular rate;
- Obvious problems with long term rotations, air bubbles, etc. must be considered and/or compensated for.

The most promising concept for low cost (<$100) and sufficient accuracy (<50 deg/hr.) is based upon micromachining technology. The state-of-the art is described in the following:

Micromechanical Gyros

Micromechanical gyros are under development at a number of laboratories, utilizing silicon-based Microelectromechanical Systems (MEMS) technology. Most of these efforts are aimed at very-low-performance (1 deg/s), low-cost devices for automotive systems. A few efforts are attempting to achieve performance in the 10-100 deg/hr range, with potential for application in flight controls and low-cost, aided navigation. Meanwhile, possible system application requirements are undergoing continuing analysis and evaluation, especially in light of increased reliance on GPS which can be used to aid/compensate the inertial sensors, making the sensor performance much less stringent and only important for shorter periods of time (<1 hr). The possible use of gyros with performance in the 10-100 deg/hr range in GPS-aided navigation can now be considered; this will likely be critically dependent on the detailed performance characteristics of the gyro, particularly short-term stability. Low-cost AHRS applications may be able to use such gyros.

Important developments are being conducted at a number of R&D facilities resulting in many instruments which are ready to test. Even more promising, but further out, work is being performed at the University of California Berkeley.

Other Gyro Concepts

In addition to Micromachining technology other long range ideas exist for low cost yet reasonable performance gyros:

- Superconducting;
- Resonating "FOG" on a silicon substrate;
- Erbium doped fiber RFOGs;
- YAG-based RLG.

Accelerometers

Accelerometer needs for GPS aided navigation are milli-g performance over a large temperature range and sensing to 40 g's. The current state-of-the-art for such demands is an accelerometer costing about $700.

Accelerometer market demands for automotive solutions are even more significant than gyros. In addition to navigation and suspension, a major demand for acceleration measurement exists for safety air bags. These concepts become very attractive candidates for low cost navigation. Side bag accelerometers (costing $10) are not accurate enough, however if a temperature compensation is performed (with a $10 temperature sensor) such a solution looks promising.

Summary

The role of inertial technology for military aerospace systems is undergoing rapid change driven by the technological advancements and commercial applications. Innovative means of integrating GPS with low cost inertial sensors such as the micromechanical gyro will provide accuracy at an affordable price. Enormous markets forces have spawned the development and production of low cost inertial instruments for commercial application that can readily be adapted for military application. These trends will continue and will be a critical enabling technology for many innovative and effective military applications of the 2020 era.

High Integrity Global Precision Positioning

G. Schmidt

Abstract:

The accuracy of satellite-based global precision positioning systems is primarily a function of the errors in the space and control segment of the system and in user equipment receiver implementation. The integrity (or reliability) of the system is also dependent on the space and control segment, on the receiver user equipment implementation, and dependent on interference (intentional or otherwise) to the broadcast signals. By the year 2020, it is expected that sub-meter accuracies will be obtainable thus allowing navigation and guidance of vehicles with very high 3 dimensional accuracy, including the vertical dimension. In addition to the high level of position accuracy provided by satellite navigation, extremely high levels of velocity and time accuracy will be achieved through closely-coupled integration with inertial sensors. However, jamming and intentional interference are expected to remain a serious issue for military operations, as well as civilian use, in spite of great improvements in satellite navigation receiver antijamming capability.

The *accuracy* of satellite-based global precision positioning systems is primarily a function of the errors in the space and control segment of the system and in user equipment (receiver) implementation. The *integrity* (or reliability) of the system is also dependent on the space and control segment, on the user equipment implementation, and dependent on interference (intentional or otherwise) to the broadcast signals. This section will discuss both accuracy and integrity.

Accuracy

The method of expressing navigation accuracy for NATO systems is the metric ninety-five percent probable error. Using this means to specify current generation, military navigation satellite receiver accuracy yields horizontal and vertical accuracies of 20 and 30 meters respectively. The *observed* performance is considerably better by a factor of two. By the year 2020, it would be expected that sub-meter accuracies would be obtainable thus allowing navigation and guidance of vehicles with very high 3 dimensional accuracy, including the vertical dimension. In fact, for guided weapon applications, target geo-location errors could be the limiting factor in achievable weapon system accuracies.

In addition to the high level of position accuracy provided by satellite navigation, extremely high levels of velocity and time accuracy can be achieved through closely-coupled integration with inertial sensors. The nominal velocity and time accuracies that are now specified at one meter per second and 100 nanoseconds will each be improved by an order of magnitude.

The path to improving current accuracies to projected 2020 accuracies includes the use of additional ground monitor stations and advanced ground-based software to generate more accurate and frequent corrections to satellite clock and ephemeris data loaded via uplinks to the satellites. The use of inter-ranging and communications between navigation satellites will be used to further refine the navigation information. Receivers will also use "all-in-view" tracking so they will be navigating using 8 satellites and perhaps up to 12, as opposed to using 4 satellites in many current implementations. Advanced atmospheric models and algorithms will also be implemented to compensate for tropospheric and ionospheric effects, as well as, multipath signals into the receiver.

Integrity

For military applications, users are concerned with the integrity and reliability of the system in the presence of spoofing, jamming, and interference. By the year 2020, implemented communication crosslinks between satellites and improved ground monitoring of satellite health status will allow almost instantaneous communications to users about failing satellites whose signals should be ignored. The wide-spread use of all-in-view receivers will allow continued high accuracy navigation even with fewer satellites. In addition, the tight-coupling between the inertial navigation system and the navigation satellite receiver will allow continued, aided-inertial navigation by tracking as few as one navigation satellite. This capability is particularly important for utilization by ground forces and in low-level aerial applications. These applications impose severe signal masking restrictions due to foliage, terrain, and urban structures. The continued use of encryption and the ability to rapidly change the military code will prohibit adversaries from generating false satellite navigation signals.

However, jamming and intentional interference will remain as serious issues for military operations, as well as civilian use. The satellites are typically in 12 hour orbits and broadcast at low power (in the order of 20 watts). Thus, very low power jammers on or near the Earth's surface could jam the received, attenuated satellite signal at the Earth's surface.

Inertial navigation systems (INS), however, are not jammable, so there is synergy in combining satellite and inertial navigation. In designing an integrated nav-sat/INS, trade-offs must be made between the accuracy and cost of the inertial system and the use of a nav-sat receiver/antenna with high anti-jam (A/J) capability with its associated cost.

Proponents of high accuracy inertial systems will generally argue that a high A/J receiver is not required while nav-sat proponents will argue that use of a high A/J receiver will substantially reduce inertial system accuracy requirements. The arguments given by both are entirely dependent on the usually poorly-defined mission and jamming scenario. However, what has generally become accepted is that nav-sat is remarkably vulnerable to jamming during the signal acquisition phase where conventional receiver technology has only limited jammer tolerability. For example, a one watt effective radiated power, continuous wave-jammer located at 100 km, line-of-sight from the nav-sat receiver antenna terminals could prevent acquisition of any satellites. A one watt jammer is "cheap" and the size of a hockey puck. Furthermore, the current civilian code can be spoofed by an even smaller power jammer. So generally, a nav-sat receiver cannot be expected to acquire the signal in a hostile environment. For long range navigation applications, the signal acquisition could be accomplished outside hostile territory and then the receiver would transition to operating in military code lock which has an higher level of jamming immunity. A 1000 watt jammer at about 100 km would now be required to break receiver lock. Furthermore, as the vehicle approaches the jammer, jammer power levels of about 10 watts would be effective in breaking military code lock at 10 km.

The military code has more anti-jam protection than the civilian code due to its ten times larger spread spectrum bandwidth. Therefore it is important to develop receivers that acquire the military code without having to acquire the civilian code. However, because the military code is very long, many seconds of time and many correlators are needed for a two-dimensional search over code timing and Doppler frequency. It would be faster if satellite ephemerides and accurate code timing were available to perform a "hot start." For a nav-sat aided weapon launched from an aircraft, accurate timing and satellite position could be transferred from the aircraft to the weapon. This transfer normally requires a wide-band data bus; few aircraft are presently so equipped. However, by the year 2020, most aircraft will be so equipped and weapons will normally be "hot-started" directly into the military code.

As new receiver technology with massively parallel correlators, improved algorithms, and adaptive or nulling antenna technologies are incorporated into the system increasing its A/J capability, A/J performance will improve significantly. If A/J performance by 2020 is doubled (in decibels), then the jammer in the previous cases would have to be 5 orders of magnitude larger to be effective at the same ranges mentioned. Such a large jammer would present an inviting target to an anti-radiation, homing missile. In the terminal area of flight against a target, the receiver will probably still be jammed and the vehicle will have to depend on inertial-only guidance or the use of a target sensor. Thus, it is important to make sure that adequate back-up vehicle guidance and navigation capability is provided to meet military mission requirements against adversaries who are willing to invest in electronic counter-measures. This fact is true today and is expected to remain so in the year 2020.

Precision Pointing and Tracking for Targeting/Fire Control

T. King

Abstract:

Precision Pointing and Tracking is required in a number of military aerospace electro-optic (E-O) application areas including: air-to-ground E-O targeting; air-to-air sensing and targeting; IR Countermeasures (IRCM) and E-O Countermeasures (EOCM). Performance improvements of at least an order of magnitude are required for weapon systems that will be in service within the 2020 timeframe. The ability to track the target is a function of the sightline dynamic performance and stability, the detector sensitivity and resolution, and the tracking algorithms.

The technical requirements for these capabilities are discussed, including: high levels of absolute pointing accuracy, pointing bandwidth, short-term pointing stability and jitter. Among the various types of solutions discussed, 'inertialess' beam-steering via electro-optic sightline deflectors provides one possible solution to the bandwidth problem. In addition, future improvements will be obtained via algorithms which incorporate 3-D terrain data closely linked to the E-O system.

Requirements

Precision Pointing and Tracking is required in a number of military aerospace electro-optic (E-O) application areas. Requirements for RF and MMW pointing are less severe because of the lower levels of spatial resolution, and their future requirements are well within the current state of the art. Hence the need for future advances will be driven by E-O requirements rather than RF.

The four principal application areas considered are:

- Air-to-ground E-O targeting;
- Air-to-air sensing and targeting;
- IR Countermeasures (IRCM);
- E-O Countermeasures (EOCM).

(a) Air-to-ground E-O targeting

There are three basic requirements:

1) High level of absolute pointing accuracy, both for long-range acquisition of pre-planned targets, and for short-range acquisition in a single-pass low-level attack, where acquisition time has to be minimised.

2) High stability and low jitter of sightline pointing, to allow acquisition, identification, and tracking.

3) Robust tracking in the presence of own-ship manoeuvre, clutter, noise and obscuration.

Absolute pointing accuracy requires close, wide-band integration of the E-O system with the aircraft's navigation (positioning) system, which itself needs accuracies to the level of a few metres to achieve instant acquisition. It also requires accurate harmonisation, which needs to be achieved automatically and dynamically in the presence of aircraft structural flexing.

(b) Air-to-Air Sensing and Targeting

The requirements are similar to those for air-to-ground targeting, with the following exceptions:

Absolute pointing accuracy is less important for acquisition, but at closer ranges the target dynamics are much more demanding in terms of pointing bandwidth. For look-down tracking, the clutter filtering problem is more severe.

(c) IR Countermeasures (IRCM)

This term, by convention, relates to self-defence against incoming IR missiles. Pointing and tracking requirements are as for air-to-air targeting, but with even greater dynamic performance requirements and rapid sightline slewing for hand-over from wide-field-of-view acquisition sensors.

(d) E-O Countermeasures (EOCM)

This term conventionally relates to directed-energy weapons for inflicting damage on equipment and sensors. The pointing requirements are as demanding as for the other applications above. Tracking may be enhanced by active means, using reflected energy from the target.

The state of the art in modern systems provides initial absolute sightline accuracy of the order of milliradians, due to harmonisation limits, and short-term pointing stability and jitter in the order of 50-200 microradian range. The ability to track the target is a function of the sightline dynamic performance and stability, the detector sensitivity and resolution, and the tracking algorithms. Performance of the

latter is difficult to express in simple numbers, but is generally a limiting factor.

Improvements in pointing and tracking performance are needed in order to extend the range and effectiveness of targeting and countermeasures systems. Improvements of at least an order of magnitude are required for weapon systems that will be in service within the 2020 timeframe.

Direction of Future R & D Efforts

To achieve the required order-of-magnitude improvements, research into a number of areas of technology advancement is required.

For Absolute Pointing Accuracy

A close integration of the E-O sensor system and the aircraft positioning system is required. This is a systems-architecture problem, rather than relating to any particular hardware. Automatic in-flight harmonisation is required, with a tight, wide-band fusion between local inertial reference and the primary aircraft position reference.

For High-stability, Low-jitter Pointing

Conventional schemes using gimballed sensors or steering mirrors will not achieve the required precision. Generally a 2-stage sightline-steering system will be required. The 'coarse' stage, using today's technology, will stabilise to levels of the order of 100 microradians. A 'fine' stage, with limited angular range, will allow corrections to the residual errors from the coarse stage. The difficulties to be overcome include:

- The bandwidth, which must be very high - several hundred Hz at least, to accommodate vibration;
- The precision of determining the relative errors between coarse and fine - largely a mechanical engineering problem;
- The availability of suitable compact, wideband, low-noise gyroscopic sensors.

Among the various types of solution, 'inertialess' beam-steering via electro-optic sightline deflectors provides one possible solution to the bandwidth problem. However, complications arise where the optical path of a laser has to be steered coincidentally with the sightline of a sensitive imaging sensor, possibly in different wavebands. For imager steering alone, 'strapdown' compensation might form the basis of the 'fine' stage. This will require advances in processing throughput capacity, although the latter is not likely to be problematic.

For High-integrity Tracking

Future improvements will be obtained via improvements in algorithms, and in modelling and analysis capability. Incorporation of 3-D terrain data into the filtering algorithms will be an important feature. The terrain database is, in any event, likely to be a required ingredient in the integrated positioning system which is closely linked to the E-O system.

The risk of non-achievement of the objectives is relatively low. Basically, the advances required will be incremental rather than revolutionary. However, they will not occur of their own accord, as the overlap with non-defence applications is relatively low.

Advanced Information Processing and Display Technologies

H. Timmers and K. Helps

(High speed processing, flat panel high resolution displays, voice activation, optical processing/networking, helmet mounted displays.)

These technologies are mainstream enabling technologies for today's aircraft and/or aircraft now in development. It is not expected that the performance of subsystems based on them will be of adequate performance to cope with increased information availability, 24-hour availability and higher performance sensors.

Specifically:

High speed processing improvements, deriving from commercial compments, will need to be available for increased data processing.

Flat panel (colour) high resolution displays in large sizes, eg. 30" X 12" will need to be adapted from, e.g. low cost field emission displays (FEDs) developed for commercial reasons in different aspect ratios, to provide an effective means for pilot situation awareness.

Voice activation will allow the pilot to operate on a broader front with displays and controls, in high workload or high-g environments, and the military requirements will not be totally covered by commercial developments, e.g. in voice environment robustress.

Optical processing/networking is an enabling technology for integrated modular avionics (q.v.).

Helmet mounted displays technology is still deficient in performance, head weight, integration with designation and head down displays.

Situational awareness. Target detection. C & C

Information and Display Processing

(Automatic target detection/acquisition. Stereoscopic synthetic enhancement techniques. Image processing for acquisition/recognition/navigation.)

For manned vehicles, unmanned vehicles and ground based stations there is an expectation that target, threat and target context related raw data will increase in quantity. It is important that the means of processing this information intelligently should not lag behind the availability of the information. Multiple sourcing of raw data provides opportunities for data fusion and confirmation and this also requires advances of treatment.

If unmanned vehicles are to be deployed more for cost-effectiveness it is important that their capability should not be too much less than that of manned vehicles.

Real-time image processing; algorithms from environmental control activities [processing power from commercial computer industry]. Multi-sensor processing.

Enhanced situational awareness. Enhanced target location. Reduced degradation by clutter.

New Information Display (Usage)

It will be increasingly difficult to maintain effective pilot appreciation of, and interaction with, the information that is available in the cockpit. Devolved authority to automation must be monitored. The problems will be more severe if measures are needed to avoid eye damage by direct energy weapons. Better usage of extended display surfaces and co-operative display devices will be required and these must be integrated with the pilot's capabilities to understand, see, speak, move and designate.

(Improvements in combining large displays, graphics generation capability, video transmission, protocol for autonomous display component compatibility, cognitive technology and speech recognition)

Combinations of technologies are necessary for mission effectiveness; large displays usage is necessary for proper pilot situation awareness and has not yet been fully explored; Graphics generation capability needs enhancing to keep pace with display size growth, and is beyond projected improvements in commercial technology which, in addition, will not have sufficient life expectancy/availability for defence requirements; Video transmission requires integration and alignment/registration with information derived from other sources, eg. map data bases and FLIR, and coping with position determination uncertainty; protocol for autonomous display component compatibility should be developed in a defence context to allow smart display subsystems to be integrated and updated readily, for cost of ownership reasons; cognitive technology could be a limiting factor in the ability of the pilot to cope with increasing information on displays and warnings; speech recognition requires improvements in speaker independence and robustness of recognition when used by stressed pilots in combat acoustic and motion environments.

Improved survivability, improved mission effectiveness, avoidance of unintended collateral damage, improved capability of co-operative missions.

Military Information Highway

J. Cymbalista

1 Abstract

" Information is power " goes the well-known saying, and the military establishment is adamant that the better informed they are, the greater their readiness to overcome foe. This, true though it be, is not enough. The example of the two chessplayers - both have thorough, perfect knowledge of the situation - shows that what gives a significant advantage is not only situational knowledge (assuming the same, high degree of access to information for both players) but also the use that is made of it, i.e. primarily how this variegated mix of data is to be processed and what strategy can be derived therefrom.

Only the transmission of information, from the time it is collected up till when it is despatched to the user, is addressed in this paper.

2 Introduction

The need for information at every level of command (at the HQ, at the command stations, with the troops on the field) is a vital one. The amount of information generated and the quantity of data required will no doubt dramatically increase in the future, to rise to tremendous heights at the time-horizon considered for the **Aerospace 2020** study.

- The number of sources will be on the rise : more sensors are to be produced, thanks, particularly, to miniaturization.
- The sources utilized will be increasingly varied, i.e. not restricted to electronic sensors, as information from a variety of sources, e.g. human sources (HUMINT), is entered.
- The data generated are to grow ever more in number, with the sophisticated sensors yielding complex data, name only the 3D hyperspectral images.
- All players will want to be informed, from the highest level of command down to the troops on the field, as this will make real-time redesign and implementation of redeployments, maneuvers, etc., increasingly flexible.

All these will lead to a very high data flow rate in virtually all directions (a point to be further detailed here). Such information system will have to be capable of quick enough (quasi-real-time), global-scale collection, processing and distribution of useful, relevant and accurate information in a secure and continuous way.

3 Nowadays Military And Civilian Situations

What is the situation these days? Already, increased demand is put on information in regions of the world and at operational theaters where sometimes no infrastructure is available to relay such data flow. This is why NATO troops sometimes resort to civil satellite communications systems that are often predominant both in developmental and technological terms (due to the cellular phone and numeric TV explosion) and in operational terms (as huge funds have been invested in commissioning those systems). Granted that those civilian systems do not offer at all secrecy, security and safety warranties required by the military, better liaise in poor conditions than not communicate at all. In this state of things, acquisition by the armed forces of satellite communications systems, as the only systems capable of liaising with the mobiles on the global scale, is on the increase. Increasingly, therefore, men on the field can be seen to open a small suitcase and deploy a 40-to- 60 cm-diameter antenna to set up a high-rate communication channel. Rather than reinvent what already exists, the military systems should try to tap the benefits from the thriving civil systems by slightly adjusting those systems so they can meet the strictly military requirements of, say, discretion, encryption, anti-jamming.

4 Military Technology Issues

A few technological solutions likely to meet the future needs of military communications at the 2020 horizon are briefly outlined hereinafter. In this, more than in any other field, technologies move so fast that the probability of erring over such a long-term prediction is formidable. The author of this paper is familiar with this difficulty and begs for the reader's indulgence.

5 Satellite Constellation

A system with a potential existence in the future is proposed in the **Air Force 2025** study. There, the U.S. Air Force envisions, three decades from now, a constellation of low-Earth-orbit (LEO) satellites called *Harvesters*, arranged in a network for collecting all data from all sources and despatching information to the final user after setting up the

adequate connections and the intersatellite routing. The data rates considered are on the order of several Gigabytes per second, and not only intersatellite, but also ground-to-satellite optical links are contemplated to ensure such data rates. The fathers of this system also envision a time-saving in-orbit-processing approach, but refrain from deciding between a low-Earth-orbit (LEO) and a geostationary-Earth-orbit (GEO) data-processing concept at this stage. This U.S. Air Force solution raises the following remarks.

- Ground-space optical transmission is problematic : despite the atmosphere's spectral " transparency " windows, it is plagued with significant attenuation, and, more importantly, with opacity caused by the cloud cover;
- The devices utilized are complicated by the beam directivity and satellite tracking requirements;
- The above drawback is partly redeemed by the discrete and hard-to-intercept characters offered;
- The possibility of illumination jamming is available to foe, as long as the jammer lies in geographic vicinity of the transmitting source.

The above remarks do challenge the credibility of such ground-space optical transmissions. Technologies won't do any good, unless the clouds can be swept away. A less daredevil, although potentially adequate solution would consist in using Ka-band RF links, say, for ground-to-space transmissions. High data rates call for rising frequencies and the 40, 60 or 90 GHz atmospheric windows could be used. However, the higher the frequency, the greater attenuation by the meteorological conditions (especially rain), and the more crucial antennas' directivity becomes. No particular problem with the electronics, as today's electronic parts can withstand up to 100 GHz and should make it to 300 GHz by 2020.

6 Compression

To those high transmission frequencies, a high data compression rate, aimed at increasing the amount of data transmitted, can be associated. Today, the algorithms used have yielded compression ratios, free from significant degradations, on the order of 10. This favorably hints at the possibility of far higher ratios two and a half decades from now. Limitation on the compression rate, it must be remembered, depends on how data are utilized. Well-known, limited number of user's need makes very high rates possible. For example, if a user wants to know the position of a tank in a picture, the highest compression rate is yielded by the sole coordinates of the tank. On the other hand, where one piece of information is to serve a plurality of users with differing needs, compression must alter the initial data as little as possible, which points exclusively at a low compression rate. It is inferred therefrom that compression has to go in two steps: first, a fairly low-rate (~10) compression process is to shrink the volume and thereby reduce the transmitted flow rate, to cater for a great number of users; and secondly, a customized, high-rate compression process enables transmission of a fairly low rate on each user's individual receiver. These steps can be accomplished on board satellites, in circumstances that require a very fast response time (e.g. anti-missile defense). In other cases, in which man's presence is required in the closed control loop and the processing time is therefore less constrained, the processes can be left up to dedicated centers. Moreover, processing by the user's individual equipment is quite a foreseeable possibility.

7 Miniaturisation

Breakthroughs in miniaturization, as it were, hint at individual equipment's capability, in a near future, to localize, transmit, receive, display, store and process with no need to be much bigger than today's handsets. This augurs well of the possibility to incorporate the said equipment to the foot soldier's wear and weapons, especially to his helmet. In all likelihood, commands will rely on voice, even the transmission equipment will use this type of commands and thus will not be distinct any longer.

8 Communication Protection

This realm of communications, it must be noted, is spearheaded by the civilian sector, and the military is bound to benefit from civil developments, making acquisition of those systems more affordable. However, the few adaptations needed for civilian systems to meet specifically military demands are to be mandatorily implemented, i.e.:

- Discretion-wise, rising the frequencies, as it reduces aperture of the transmission lobes, is a good contributor.
- Message intercept/decrypt protection is provided by :

  * the dedicated compression algorithm and the spread spectrum (CDMA) technique, which both provide only limited protection;

  * the narrow spots, which globally provide coverage of the considered zone;

  * most importantly, encryption.

- Thin-beam coverage of the zone is another anti-jamming method, as communication can continue in all other beams exclusive of the one where the jammer is situated.

- The foe must be prevented from using the system, whether for its own purposes or with a view to pollute information; to that aim, checkout and authentication techniques that raise no real hardships have to be implemented.

- The system must be immune to physical aggressions, which calls for some hardening, as well as for some scattering and redundancy of the units; the system will thus remain serviceable even in case of destruction of one of the network's nodes. In this respect, the principles that will apply in 2020 are the same as today's, with the little plus that the network will have become intelligent by then, i.e. capable of automatic rerouting.

9 Communication Links And Rates

A clear distinction must be made when it comes to data flows : while no doubt quite significant when directed at the men on the field (possibilities of some hundreds of Mbits per second) they will be far less the other way. To address this aspect, a GEO satellite system offers the following advantages over an LEO approach :

- Fewer, more controllable GEO satellites are needed for a global cover;

- While both systems are, of course, capable of beaming high flow rates to the operations theater, LEO is more prone to jamming than GEO;

- Since flow from field theater to space is comparatively small (essentially voice communications), the demand on power to ensure a proper link budget is small;

- Yet another advantage is the ground systems' capability to accurately point at a fixed position in GEO, and thereby focus the required power in one direction, which makes them more simple, more compact and more discrete;

- Sufficient power to link up the infantryman to the GEO satellite (where high rate is needed, for images transmission for instance) can readily be secured by relay mobiles that provide a small-size proximity cellularity.

For the sensors, which are potential generators of high rates (imagery purposes), wide use of space- or airborne solutions will make high data rate transmission to the GEO satellites a fairly smooth affair.

The quarter-second lag due to ground-to-space back-and-forth propagation is no real GEO drawback compared to an LEO solution, since few (if any) actions require a response within the periods of time for which 0.25 second is penalizing, let alone the case of man's presence in the loop, as in many data-handling and/or decision-making processes.

10 Other Issues

As for the vulnerability of satellites, although LEO solutions have often been said to be more vulnerable than GEO ones due to greater proximity, it is fairly easy to place antisatellite (ASAT) weapons into geostationary Earth orbit with the mission of making a communications satellite inoperative in due time. To be noted, a pyrotechnic device is not suited to this purpose, as pollution from the explosion-induced debris throughout the satellite's geostationary orbit would be potentially adverse to friend as well as foe satellites.

Needless to say, those advances in communications systems are not likely to be achieved unless adequately funded. For the space segment, in particular, if the costs of civilian systems - which total billions of dollars - and, on the other hand, the European countries' comparatively modest investment in military space communications are any guides, serious doubts can be cast on the hope of seeing such evolutions materialize at the foreseen horizon.

One should not forget that space technologies' life cycles far exceed on-ground technologies', due, in particular, to the time consumed by parts qualification. This calls for space technologies that are sufficiently innovative and adaptable to keep pace with the ground systems' evolutions.

11 Conclusion

Telecommunication is a domain where technologies are evolving so quickly that it is difficult to foresee even ten years in advance. What is sure is that the need for more information and thus transmission rate will increase. It is considered some hundred of Mbits/s and even more. As far as mobile communication is concerned, no doubt that a major part of the transmission links will use satellites which is the only system able to cover the whole globe, thus to be operational in any part of the world, able to connect people without delay even where no infrastructure exists and to transmit high data rates. In the same time, the personnal communication equipment will be miniaturized, completed with many sensors and will be integrated in the soldier's wear and weapon.

Most of these future technologies are already studied, and perhaps all that will happen well before 2020 if adequate funding is available.

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Fault Tolerant Highly Integrated Avionics Architectures

H. Timmers and L. Ott

Objective

Avionics is approaching 40% of the weight and cost of the aircraft. In order to reduce weight, cost and maintenance actions and provide affordably increased functionality, a highly integrated commercial-off-the-shelf (COTS) based avionics architecture must be developed. This architecture will be characterized by its modularity, resource sharing, fault tolerance attributes and wide use of commercial components. The overall dependability and fault tolerance of the next generation of highly integrated, COTS based avionics systems will be a critical factor in the effectiveness of those systems in future combat scenarios. Thus the challenge is to demonstrate and validate that this high integration and the military real-time, fault tolerant and security requirements can be met with CTS/open system components.

Payoff

This architecture will reduce the cost of upgrades due to it's modularity and wide use of commercial off the shelf components, reduce mission aborts and maintenance actions due to it's fault -tolerance, and reduce weight due to the integration and sharing of a number of digital functions (processors, displays). Furthermore the openness and flexibility of the architecture should allow for quick reconfiguration of the aircraft for different missions thus truly providing a mufti-mission aircraft. The architecture can be applied to both manned and unmanned aircraft providing significant cost savings since it is being incorporated to many aircraft.

The current generation of avionics has low Mean Time Between Failure and high spares usage. This fault tolerant highly integrated architecture aggressively addresses the problem of designing and validating dependable avionics systems using COTS/open system parts and decreasing the high MTBF and high spares usage of current systems, If the fault tolerant highly integrated architecture efforts are successful, they will enable future avionics systems to achieve the goal of developing an affordable COTS/open system avionics systems capable of 60 days sustained availability without maintenance with an overall decrease in A/C downtime thus increasing system availability and pilot/vehicle interface and workload.

Description

The work in fault tolerant highly integrated architectures is aimed at verifying a complete distributed avionics system from hardware to a concurrent programming language that enables the system to automatically reconfiguration, gracefully degrade in the presence of hard faults or minor battle damage, and dynamically allocate tasks to available processing resources depending on the mission and the current mission timeline. The frequency of hard fault rates is decreasing for both military and commercial digital parts but transient fault rates are increasing. The next generation of avionics systems needs to automatically handle transient faults and notify the operator only when recovering from hard faults, yet record all fault activity to ensure quick diagnosis of failing parts. Particular attention is being paid to the verification and validation of these highly integrated COTS based avionics systems to ensure they meet military real-time, fault tolerant and security requirements. This demonstration and validation testing will determine if software mechanisms can adequately compensate for the less reliable COTS resources and enable the system to deliver it's specified real time, fault handling and security services Validation can be accomplished in three ways: (1) by exhaustive testing, (2) by formal analysis, or (3) by a combination of the first two. To exhaustively test the systems would take years of computer simulation or breadboard time, therefore the third approach is being used to ensure a reasonable turn around time. Formal methods are being used to analyze the key algorithms of the system and based on this formal analysis an adequate and sufficient test set is selected to verify the real-time, fault tolerant and security features of the fault tolerant highly integrated architecture. Formal methods are a key area in the current fault tolerant highly integrated architectures efforts. Formal methods are a set of tools and notations that are used to unambiguously specify the requirements of a computer system and to demonstrate that absence of bugs in that formal specification. They are used in systems where the highest integrity and dependability is required. Formal methods notation unambiguously specify the required properties of the fault tolerant highly integrated architecture and then those properties are mathematically verified for correctness. A test set is then formulated based on the formal specification and this test set is used to verify that the prototype system contains the properties of the formally verified specification. This approach will lead to fault tolerant highly integrated architectures in which the military real-time, fault tolerant and security requirements can be met using COTS, open system components.

In addition to the fault-tolerance another important aspect of the architecture is its openness. This feature

will allow easy insertion of new COTS hardware/software allowing increased functionality affordably. Modules from different vendors will be inserted in a standardized backplane. A unified photonic network will not only replace the existing wire busses but will allow the transmission of gigabytes of information around the aircraft and provide a reconfigurable capability in case of component failure or to prepare for a different mission. .Emulators will allow the mixture of old and new software that may be written in different languages.

Technical Issues

The commercial parts and open system standards that will be the major building blocks of the next generation military systems were not designed with critical military real time, fault tolerant and security requirements in mind. Therefore the key technical issues facing the current designers of military systems are:

- How can these COTS components be used and still maintain military real time/ fault tolerant requirements?
- What can designers of future military avionics systems do in node and network system software to compensate for these less reliable, non-Mil Spec, COTS/open system resources?
- What system services are needed to compensate and adequately manage these less reliable system COTS resources and what features are needed in those services?
- How can defense labs in the future adequately test these future avionics systems to validate that they meet military real, time/fault tolerant and security requirements?
- What system design features need to be implemented to ensure that there are no common mode faults among multiple modes using the same COTS operating systems?

Status and Future Actions

A number of demonstrations are planned with the goal of validating and deploying COTS, open system, highly integrated avionics at the beginning of the next century. Program offices developing this next generation of weapon systems urgently need the answers outlined in the technical issues section in the coming years to ensure reliable and dependable performance of the next generation of COTS based avionics systems If these fault tolerant, tightly integrated, architecture efforts are not effective the next generation of avionics systems will have increased MTBF, spare usage, low availability, undependable mission performance, a high number of mission aborts and it will significantly impact overall combat effectiveness. Thus, an aggressive effort is under way to design and validate a fault tolerant tightly integrated architectures that will reliably deliver its expected fault tolerant, real-time and security services in future combat scenarios.

Adaptive Real-Time Guidance Techniques

P. van Turennout and M.A.G. Peters

1. Abstract

The identification, targeting and kill of critical targets, particularly targets that are mobile, is of extreme importance to the success of missions. To accomplish this, *capabilities* such as real-time mission (re)planning, location and identification of targets and real-time weapon guidance are required.

Technologies needed to accomplish this are real-time data base management, fusion of on/off board data, algorithms for the detection and identification of targets, significant processor and memory capabilities and means to allocate these resources in a flexible manner.

2. Introduction

During its mission, an own platform (whether it concerns an aircraft, helicopter, ground station, ship or mobile ground forces) will be supported by other platforms, each with their own dedicated sensors and data processing capabilities as necessary for their own specific mission. For example, a command and control centre may not have its own sensors, but will dispose of a large processing capacity to process incoming data from several sources, which data is available through a high-speed data link communication network.

This paper focuses on the aspects of the detection, location and identification of targets on a single platform (possibly assisted by communication from other platforms) to facilitate mission (re)planning and weapon guidance. The following topics are addressed:

- Sensor data processing;
- Data base contents and management;
- Flexible allocation of resources.

3. Sensor data processing

1. Starting point for high-precision targeting is the availability of sensor data on possible targets. The following steps are involved:
2. Target detection and tracking by the own sensors, possibly assisted by off-board data from command and control centres, other platforms and/or intelligence information. *Data fusion techniques* are used to reach the necessary accuracy's and reliability's.
3. Identification/classification enhancement for better threat assessment. This is achieved by *information fusion*, which is to be seen as an extension of (traditional) sensor data fusion.
4. Guidance support through the generation of synthetic imagery from data of individual (imaging) sensors: *image fusion.*

3.1 Data fusion

There is a need for combining sensor data from multiple sensor systems into an integrated representation of the sensed environment. Combining sensor data will enhance system performance and effectiveness when using complementary and/or redundant sensor systems compared to single sensor systems. By combining the data from several sensors, 'virtual' sensors are created. The contributing sensors may be based on different technologies; in that case the virtual sensors may also be referred to as a 'multi-technology' sensors. The benefits for applying sensor data fusion can be described as follows.

- Accuracy improvement: a target's state vector (position, speed) can be obtained with smaller uncertainties (in tracking) and also targets can be detected with a higher probability (the more sensors report a similar observation, the more likely these observations belong to one and the same target).
- Extended spatial coverage: use of more sensors allows the observation of targets at larger ranges and wider FOR; also, an extension in the dimension of a target's state vector can be obtained (e.g., from 1-D to 2-D or even 3-D measurements).
- Higher availability (continuity) of data (i.e. extended time coverage): operating conditions (e.g., atmospheric, or the presence of ground clutter) may inhibit the use of certain sensors, but it is less likely that such conditions inhibit the use of all available sensors at the same time. Degraded operation of one sensor is compensated by other sensors. Also, when active sensors are blanked, passive sensors can continue their operation.
- Robustness: the sensor system as a whole is more robust against degraded sensor operations, adverse weather conditions and against jamming and/or spoofing. As a result the own platform is less vulnerable.

To which extent these objectives are reached, depends, of course, on the (combinations of) sensors

used. Other benefits resulting from sensor data fusion are:

- Reduction of data into (more) reliable, concise and surveyable information to be send to other platforms, including command and control centres;
- Improved situation awareness and a reduction of work load for an end-user;
- Reduced data communication needs (the original sensor data can be transmitted as well for backup or background information, but at a lower rate and/or priority).

3.2 Information fusion

By the use of data fusion techniques, data from the different sensors and different vehicles can be combined to increase the accuracy and reliability of knowledge on not only the state vector (position, course and speed) but also the identification of tactical objects. The goal is to have each object described by one 'virtual' observation instead of by a number of observations from several sensors. The more a identification/classification given by one sensor (with a certain reliability/probability) is supported by other sensors and/or platforms, the more reliable/probable this classification will be.

Clearly, sensor observations must match in position, course, bearing and speed (all within certain margins, to account for errors and uncertainties). Also, it is very important that identification properties do not conflict (e.g. a 'friendly' object should not be associated with one marked as 'hostile', or an association of a land-based vehicle with a vessel near the coast). A match in secondary identification properties (so-called 'amplifications') can increase the confidence in a correct association.

In particular, intelligence information can be used to enhance the association process. For example, when the ESM detects a certain type of radar, one can use the intelligence information to look for vehicles/objects known to be in the operational area, which utilise that specific type of radar. Combining this information further with the available data, will support the operator in providing a (better) identification of that particular object.

3.3 Image fusion

Poor outside visibility and darkness associated with night time is very often the cause of restricting various operations, especially those allied to (military) aviation. Currently there is much debate about the possibility of using advanced vision systems (AVS) to augment the operator's image of the environment around him; this would enable him to be aware of obstacles and terrain in his flight path just as in good visibility conditions. One of the basic goals is to enhance safety, in addition to efficiency and operational capability for civil and military applications. It is anticipated that the recent proliferation in vision system technology is likely to provide opportunities to resolve some of the current constraints associated with both the civilian and military transportation infrastructures, whether land, air or sea based. The magnitude of the contribution offered by new vision systems technology in any of these latter areas will of course differ, especially as its use for civilian applications is relatively new.

Currently there are two potential candidates for AVS, which may be used independently or in combination. Very broadly speaking Enhanced Vision Systems (EVS) use electro-optic sensors and/or radar to generate an image of the surroundings. The second option, a Synthetic Vision System (SVS), involves generating video images by integrating primarily navigation data from appropriate sensors and a (digital) terrain data base.

Although the concept of EVS/SVS is not new, the ability to implement this technology in a useful and cost effective manner is now a more feasible challenge. Developments in sensors, image processing, and microelectronics during the last two decades contribute to this feasibility. It is expected that at the turn of the century and the coming two decades AVS systems will become common use.

4. Data base contents and management

The on-board data base should contain a variety of relevant data, such as:

- Tactical data (target tracks, identification information, intelligence data);
- Target signature libraries (corresponding to on-board sensors);
- Platform libraries (platform characteristics, platform-weapon correlation's);
- Terrain database for navigation (terrain following), mission planning and synthetic vision;
- Informative data: plain or formatted text relevant to the mission, the area or expected targets.

These data should be accessible in a flexible way, such that mission-dependent data can be loaded not only before the start of the mission but also during the mission. This can be achieved through the use of (solid-state) data recorders to retrieve static data (e.g. terrain data/maps) and through high-speed data links for time-critical data (i.e. uploading from command and control centres).

Although all the data base functions require much processing and memory capacity it is not expected that the limitations will be in these areas as progress in processor speed and memory capacity is tremendous. The requirements for processing power, distributed processing and distributed data management will be driven by the commercial and industrial field. The same might be the case in the area of displays (multi function displays and/or helmet mounted displays).

5. Flexible allocation of resources

Flexible allocation of (common) resources is of prime importance for a successful execution of the implemented functions. The focus is on 'common' to hold down cost, mass, volume, power/heat and to provide for interchangeability and maintainability. Another feature is automatic/dynamic resource allocation to provide for delayed maintenance and to augment system availability.

These techniques are being studied in numerous (international) research programs (ASAAC, EUCLID, EU) to ensure 'common modules' for hardware, software and communication. One example is the research program RTP 4.1 entitled Integrated Modular Avionics (IMA).

These features of IMA can be extended to allocating available resources based on the needs of the current phase of the mission. For example: initially, while approaching the mission area, processing resources are dedicated to (tactical) navigation and mission (re)planning based on the latest information from command and control. In the mission area, more resources would be needed for sensor data processing. In particular, combinations of sensors (and the appropriate fusion of their data, resulting in a 'synthetic' sensor) could be made depending on the types of targets or environmental conditions (terrain type, weather, day or night). With such an optimal 'synthetic' sensor targets are being detected and tracked.

An Integrated Modular Avionics (IMA) architecture also takes into account that, in a rational architecture, the normal operating mode should not make use of the full 100% of the computational resources (i.e. CPU time is not fully used, memories are not fully allocated). We may thus see the unused resources as spare and redundant ones. When a failure occurs on a computational unit and no spare units are available, all the workload of that unit may be decomposed (where possible) and re-allocated in other different computation units.

6. Conclusions

In summary, improved capabilities to reach real-time (in-flight) mission (re)planning and to quickly adapt platform and/or weapon guidance with respect to high-precision targeting are supported by:

- Combining data from different on-board sensors to achieve more accurate and more reliable target detection and tracking ('virtual' sensors concept);
- Combining on-board data from ('virtual') sensors with off-board data through data links to increase time and spatial coverage and improve target identification;
- Combining image sensors to improve guidance by night or in adverse weather conditions;
- Flexible (re)configuration of processing and memory resources to mission dependent functions. For example, creating or changing optimal configurations of 'virtual' sensors in the data fusion process based on target characteristics;
- High-speed data link connections to allow real-time support from command and control centres (for extensive processing tasks and decision support) and/or other platforms. Also for uploading of information to the on-board data base;
- Advances in on-board data storage capabilities (e.g. solid-state data recorders) and display technology improve the capabilities to have access to large and/or detailed terrain data (from reconnaissance sensors, for example) and to display and edit this on high-resolution cockpit displays.

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Integration of Technologies for Closed Cockpits

H. Timmers and K. Helps

All future aerial missions are threatened by directed energy weapons (DEWs) or flash devices. The availability of rather inexpensive blinding flash devices can soon significantly hinder or even prevent the effective use of air power. In order to protect aircrews and enable them to successfully continue the mission the concept of closed cockpits will be an important means to overcome these threats.

Processing capabilities which will be available in the near to midterm future make the realisation of closed cockpits feasible. Still, the closed cockpit impose some severe problems which must be solved in order to maintain crew awareness under all circumstances and in all phases of flight. To name only a few of them, problems associated with synthetic vision, sensor displays and sensor integration or pilot interaction with all aircraft systems must be solved to make the closed cockpit concept operational viable. It must be proven, that sensors can be built, which work reliable under all conditions (including massive counter measures), that all available data can be fused together and that all these sensors can be integrated in a way to give results which can be trusted and effectively communicated to the aircrew.

The realisation of closed cockpits is a task, which requires contributions from many other technology fields, hence, it works as a technology driver also outside it direct field of application. The benefits of the closed cockpit will be the ability to perform aerial missions also in presence of a new class of threats successfully.

Commanders' Decision Aid for Battle Planning and Execution

P. van den Broek

1. Statement

Powerful computing equipment will enable the prediction of the evolution of a complex process as a battle mission, and much faster than real time. This will be used to evaluate the effects of changes in battle plans, both changes in battle tactics and changes in allocated assets.

2. Mission Planning

A commander's problem is to define an attempted mission profile such, that given the actual tactical situation, 1) a given goal is reached for a minimum effort, 2) for a given effort the maximum result is or 3) the best ratio between goal and effort is realized. The mission definition consists of the determination of the required effort, mainly required assets, and anticipated the evolution of the mission, for a given tactical initial situation.

The starting point for the mission planning process is the tactical situation. Elements of the tactical situation are 1. data on the target, 2. geographical or terrain data, 3. data on the threats along the route to the target and 4. information on the availability of potentially required assets. Then various options for mission profiles are conceived. This involves the selection of the weapons to be used to destroy of the target, the selection of the weapon carrier and, taking into account the terrain condition and the threats in the target area, the selection of the weapon release process. Furthermore, the route to the target area has to be selected and the use of assets, additional to the actual weapon carriers, such as electronic warfare, mission allocated reconnaissance and tankers. From the available options the best one will be selected. After this, the detailed tasking orders will have to be derived, the mission will have to be performed and the evolution of the mission should be monitored. And finally, if something unforeseen happens, the mission execution may have to be adapted to the new tactical situation.

In this process a number of selections have to be made. In some cases, a choice has to be made from a very limited number of options, but in other cases many options are to be considered. Combining all options for all choices will result in a large number of more or less different mission profiles. The classical way to handle determination of the mission profile is based on professional skills. Based on the knowledge acquired during education and training, and from experience he may classify the tactical situation and decide on a mission profile. By assessing the situation he may determine the assets, necessary to perform the mission successfully.

3. Networking

The starting point for the decisions on missions, or the generation of tasking orders, is the tactical situation. To form an overview of the situation relevant information, concerning on one side the friendly forces, which may be cooperating in a joint action or spread over a number of task forces, each performing its own sub-mission, on the other side, the opposing forces and their locations, movements, strength and equipment, and in between, the terrain, with its permanent features and time varying features, and the weather. The commander will consider all this information, make his projections for an anticipated mission, weigh the various factors in order to come to a decision.

The required information will be available, but it will be spread over many different places. Some of the information will be available close to the area of the anticipated action, but some will also be at a larger distances, up to intercontinental distances. To reach the best decision all relevant information should be at the disposal of the commander. A world wide, military, secure communications network will provide the channels to transport the required information to the place of the decision making.

If the commander is located close to the weapon carriers and other units participating in the mission, the commands will be transmitted directly to these units. For a larger mission, involving units located at a larger distance commands, or sometimes requests, will have to be transmitted to these units. Then the network will also be used to disseminate commands from the commander to his units.

Lastly, the network will be used to inform other friendly forces, information and intelligence agencies and higher command and control centers in order to enable these to coordinate his actions with other missions.

4. Mission simulation

In the future, computer technology, and in particular networking and computer simulations, will change and speed up this process considerably.

The evolution of a military mission is certainly a dynamic process, where a variety of different units, ranging from individual vehicles to complete strike packages, are moving following certain rules. The units of one party will be mutually cooperative, as will be the units in the opposing party. Of course, the parties themselves are non-cooperative. The rules, describing the motions of the various units may be rather deterministic, such as the rules describing the

motion of an aircraft, or more fuzzy, such as the rules for a more complex unit as a strike package. In any case, the rules for the motions of the units can be expressed by mathematical (differential) equations, that can be solved by a computer. Of course, the quality of the results will depend on the fuzziness of the rules and thus on the fuzziness of the differential equations. Furthermore, the quality of the outcome will also depend heavily on the quality of the data, and thus on the available information, taken as input to the calculations.

In a simulation of a military engagement the equations for the own units, as well as those for the opposing units will have to be solved. The equations for one unit takes into account the characteristics of the units itself and the effects of the environment on its motion, such as the terrain characteristics and the weather. Furthermore, each unit will react to command and instructions from its own side and on threats or possible actions from the opposing side. For the simulation of an engagement the equations for the participating units have to be solved simultaneously, taking into account the mutual interactions between the units.

In military engagements different scales can be distinguished. A large scale action would involve a larger or smaller number of strike packages or strike forces acting in a larger geographical area. A small scale action would involve the action of an individual strike package. Analogously, simulations can be performed at different scales. In a simulation of a large scale engagement the participating strike packages are the units to be considered, and the simulation process should take into account the interactions between these packages, and the larger scale environmental items. The interactions between the sub units inside each package should not be taken into account. Also the individual threatening air defence units, as guns and fighters, will not be regarded. On the other hand, if the mission of a single strike package as such is simulated, the detailed level interactions between units inside the package and the individual opposing fighters and gun sites are of prime importance, but in that case the interactions with other strike packages is out of the scope of the simulation. As a consequence, the computational effort to perform a simulation will be of the same order of magnitude in both cases.

As a matter of fact, the computer power required to perform such simulations, as far as the hardware is concerned, is already available. However, missions, and in particular larger scale missions, are complex dynamical processes, that are not yet readily understood. Formulation of these processes in a form that enables computer simulations is at least a few steps beyond present day capabilities. Development of the software for these simulations will require much analysis effort to reach the possibilities, sketched above by the year 2020. The way to go may be as follows.

Decision aiding systems at the lowest level, and the associated simulation technology, is available at this time in systems as 'the pilot's associate'. Starting from these models mathematically simplified, overall input-output relations for these vehicle-level units may be derived. As a next step these units will be combined in higher level simulation algorithms. If this stepping-up process is performed a number of times, each time comprising larger overall missions, it will be possible to simulate large scale missions.

5. Simulation applications

The described mission simulation will be applied to aid the decision making process in various ways.

One application is the assessment of the effects of variations of mission parameters for an intended military engagement. To this end a number of simulations assuming different options are run and the results are compared. Based on intelligence information a sufficient knowledge of the initial tactical situation is available, but the tactics to be applied and the assets to be deployed has to be determined. To compare the various options a number of simulations will be run for different combinations of tactics and assets. For each combination the military effects are quantized and the related costs in terms of required assets are estimated. From the various options the best option is selected. A characteristic of this application is that each simulation run has to be performed in a short time. This will require a computer system with sufficient computing power. However, the requirements are certainly not excessive. In this application the simulations are performed to enable comparisons of options, thus the differences in the simulation results are more important than the magnitude.

The other application of simulation is the verification that the adopted option for a mission is in detail feasible. This implies also the determination of the details of the sub-missions that constitute the overall mission, such as the task description, including the target description and boundary conditions for the sub-missions and an estimation of the composition of the task forces to perform these sub-missions. This goal will require a rather limited number of mission simulations. From the first mission analysis, the comparison of options, a selection is made. This defined mission is simulated in some more detail, because in this case the results have a quantitative significance. However, if the first adopted mission profile is correct, only one simulation may be sufficient. In practice, it may be expected that some adjustments in the details will have to be made, so that a few additional simulations will be required.

Mission simulations, both for tactics analysis and for evaluation and quantification, will be used in decision aiding at different command and control level.

At one end of the scale it will be helpful a large scale engagement analysis. This results in a overall tactics of the anticipated engagement. Additionally, it yields a list of units, as task forces, participating in the total engagement and other large scale assets. Each task force will also be assigned an individual mission task, the initial conditions and the specifics of task to be performed. A logical next step is to use similar simulations to aid in making the decisions on the level of the task force mission. These simulations are performed in much more detail, involving the movements of individual vehicles. This procedure will be repeated at the next lower level, which may be the missions for each individual vehicle or weapon system, of groups of vehicles or weapon systems. Then the mission description will be reduced to the task to attack or destroy a specified target and return to base.

For this relatively simple case the role of simulation can be illustrated easily. Simulations can be used to determine the optimum route to the target, to calculate a number of alternate routes, and present these visually in relation to the various threat, so that the best route can be selected. After that, the anticipated mission can be evaluated by a hardware, pilot in the loop simulation, and thus rehearsing the mission.

6. Automation of the decision preparation

In the preceding sections the application of information retrieval through an information communication network, and simulation for decision aiding is sketched, where the commander has full control of the information flow and the simulations to be performed. If decision are to be made on larger scale mission the information to be considered and the simulations to be run will soon be too much to handle fully manually. Therefore, computer technology will also be used to reduce this type of workload.

In a more sophisticated scenario, relevant mission defining data, such as place and type of the target will be the input to a knowledge based system. This system will decide by itself which additional information is required and where it is available. Automatically or if instructed on line, the system will perform the actions to acquire this information from where it is available. Next, again either automatically or on instruction, the system will start various mission simulations. Finally, the computer will present the results, in the form of alternatives for missions, if required provided with comments or specific advice, to the commander.

The system can aid the commander in decision making on various levels of autonomy. At the stages of the process where a decision has to be made, the system could provide various options in an arbitrary sequence, from which the commander can choose. In that case he has to compare the merits of the options entirely by himself.

If quantitative rating parameters can be defined, such as the number of target hits or quantities of assets, the system could present options in a corresponding ranking order. Then the commander could decide to have a closer look at the most promising options, being the top two or three of the options list, or he could simply take the top option. In many cases it is not possible to define quantitative rating parameters. Then more sophisticated technologies will be applied, in particular knowledge based systems technology. Also in this case the system could present a ranking order in its results, which will aid in the decision making process. However, as the ranking is based on more loosely defined criteria, the system will also have to present its reasoning.

This computer interfacing action, to find and present alternatives or options and subsequently making a decision which determines the evolution of the remainder of the mission development process, can be applied at various places in the process. These places could comprise: 1. the decision which intelligence information should be retrieved and from where, 2. which simulations should be performed to be compared, 3. which concept mission should be selected and subsequently evaluated and finally, 4. the adoption of the final mission.

In principle, the decision making can fully be automated, by instructing the system to take the top ranking option at each decision. This requires fairly accurate descriptions of the criteria for the ranking of the options. However, human beings will always be responsible for whatever decision, and certainly the final decision on a mission. Therefore, even if a part of this process is automated, the system will have to provide a complete insight in all the factors that affect the decision. This latter requirement put rather heavy demand on the presentation of the information. If the decision is to be made by a human commander, the presentation should be such that a complete insight is given in the various options, if decisions have been made by the system, the underlying reasoning has to be made clear.

7. Presentation of results

As mentioned in the preceding section, an important item in the decision making process is presentation of information. The information may concern tactical information, retrieved via the network from intelligence agency or the results of mission simulations. The presentation of quantitative data,

e.g. to compare the results of a number of simulations, the end result may be presented in the form a few numbers. The comparison may be eased by displaying the data graphically. This may be used initially to decide on the general tactics to be exploited for the mission. This type of presentation is not very demanding and in fact it is already widely used.

A slightly more complex type of presentation is that, where different related types of information is combined. An example could be the presentation of the location and the character of various types of threats is a battle area, combined with geographical data. Then the presenting picture will be more complex, and it may require more preprocessing. Nevertheless, the picture is still static and as such it is not demanding either.

In the future the presentation of dynamic information will become important. Dynamic information is information about moving processes. This could concern the evolution of an anticipated mission. The evolution is predicted by a mission simulation and the simulation results are presented as a time sequence of events. A relatively simple way is the presentation on a large screen. As a matter of fact, this is applied already in vehicle simulators to present the environment visually.

A similar presentation can be used for an actually on going engagement. Information on the movements of the own forces and, as good as possible, about the movements of the opposing forces could be provided on a near real time basis by the appropriate agencies via the secure military network. This information could be edited and subsequently presented visually.

Virtual reality is the key technology which will enable a visual presentation of the evolution of actual or simulated mission in a very realistic way. Using digitally available terrain data, the evolution of the mission in the terrain may be presented, thus giving insight in the critical details or mission phases. The commander will be mentally involved in the proceeding of the action. Additional information, such as threat areas and threat shadowing, may be superimposed as a symbolic, virtual realization overlaying the visual presentation of the real battle environment.

However, one should be aware of the technology threat. By the year 2020 the technology will be available to present whatever available data to the human operator or commander in any desired visual form of virtual reality. But presentation of too many details of the terrain and the additional data will be confusing. This can be eased by simplifying the presentation of the real environment to the significant information. This will require extensive use of knowledge based technology and other, still more sophisticated forms of artificial intelligence to separate the essential information from the extra information, for a variety of different cases.

8. Conclusion

Information networks, mission simulation and virtual reality technology will enable relieve the commander from much workload by the presentation of any desired type of information in any quantity to the commander, but it should be kept in mind that all the decisions remain the full responsibility of the commander himself. The system, however sophisticated, has to provide all the possibilities to live up to this responsibility.

Advances in Supporting Technologies

U. Krogman

1. Advanced Information Technology, High Speed Processing and Networking

1.1 Computational and Machine Intelligence

There is a paradigmatic complementary shift from symbolic AI/KB techniques to so called soft-computing technologies. The new paradigm is based on modelling the unconscious, cognitive and reflexive function of the biological brain. This is typically accomplished by massively parallel implementation as compared to program/software based Information Technology (IT) in conventional sequential architectures.

In contrast to the conventional methods, soft-computing addresses the pervasive imprecision of the real world. This is accomplished by consideration of the tolerances for imprecision, uncertainty and partial truth to achieve tractable, robust and low cost solutions for complex problems.

Important related computing methodologies and technologies include among others fuzzy logic, neuro-computing and evolutionary and genetic algorithms.

The theory of fuzzy logic provides a mathematical framework to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning. Also, it provides a mathematical morphology to emulate certain perceptual and linguistic attributes associated with human cognition. Fuzzy logic provides an inference morphology that enables approximate human reasoning capabilities to knowledge-based systems.

Neural Networks are derived from the idea of imitating brain cells in silicon and interconnecting them to form networks with self-organization capability and learnability. They are modelled on the structures of the unconscious mind.

Genetic and Evolutionary Algorithms are based on the mechanism of natural selection and genetic evolution which offer search, optimization and learning behaviour.

It has become increasingly evident that combinations of these technologies are advantageous in many applications. A viable step towards intelligent machines can be expected that offers autonomous knowledge acquisition and processing, self-organization and structuring, as well as associative rule generation for goal oriented behaviour in rarely predictable scenarios.

There will be neurocomputers (in 5 to 10 years) whose capacity will be approximately equal to that of the biological neural network of an insect (one million neurons, one billion synapses). They will be implemented electronically or optically (cubic centimeter volume).

If the capacity of electronic computers continues to double within one year, digital neurocomputers will quickly advance towards the range of up to 5 million neurons and 10 to 100 billion synapses. However, this will require development surges in the field of nanoelectronics.

The benefits from new computational and machine intelligence will be manifold, e.g.

- Reducing the need for manpower while improving the response times of humans plus their intelligent support systems,
- Removing crews from hazardous environments and exposed platforms, i.e. improved survivability,
- Enabling intelligent fault-tolerant self-diagnostic on-line and off-line systems which improves readiness and availability and which reduces procurement, utilization, maintenance and logistics costs,
- Learning capability alleviates the tasks of programming and thus reduces software generation and maintenance costs while reducing development time.

1.2 From Conventional Architectures to Networks

Although the development of hardware and software for computers of conventional v. Neumann architecture has continued for more than 20 years and the performance of today's processors is 25.000 times better than in the 1970s, the dynamics of this development is going on as well.

Today a microprocessor based system costs 1/40th as much as its ancestors of the 70s. The result: an overall cost-performance improvement of 1 000 000! This is why computing plays such a large role in today's world. Processor performance will continue to double every 18 months. These breathtaking advances will put enormous computing power into future mission systems.

Along with processor technology, quantum leaps in electronic design and manufacturing will reduce the necessary volume, weight, power and cost of computer systems. By the year 2000 there will be

chips with 50 million transistors running at more than 500 MHz. A similar picture can be predicted for advances in the storage technology. A PC of today's pentium class, for instance, will be accommodated on a chip card.

High performance on-board computing will be obtained by the arrangement of scalable parallel computers in network structures. Powerful optic switchable network links will connect several networks to form large cooperative network structures. The hierarchically supervised performance of these structures will be augmented by a goal oriented learning feature.

The big goal in Supercomputer evolution is the „3T machine" with a terabyte of memory, a teraflop of computer power and a terbyte per second bandwidth between the CPU and the memory. In combination with advanced communication a number of these machines will be connected through networks which will have unprecedented computational power. By the early 2000's supercomputers of several teraflop/terabyte/terabyte per second will become available. By the year 2020 one can envision supercomputers even 1000 times more efficient if hardware, architecture and software technologies are advancing at current rates.

1.3 Advances in Software Technology

Huge advances in computer and communication technology will provide enormous processing, storage and data exchange capacity. In addition the amount and complexity of information available on and off platforms will be immense. Software will have the task to make use of these huge resources and providing the functionality and automation necessary to support humans or even to replacing humans in the handling of information and performing optimal missions.

Software will be structured in layers of functionality. The interface between these layers will be standardized (like today's network protocols). The standardization of layers will be essential for the successful development of highly complex mission systems, where different functions interact closely on the computer networks. These software structures will allow the retention and upgrading of most parts of the software during replacement of the hardware.

High order programming languages will enable to express the functionality in a much more application specific manner than in today's systems. Real time aspects will be embedded in the language and be supported by the operating system. The application functions will be based on powerful lower level software that manages the safe separation and integrity of functions and the fault management and real-time automatic reconfiguration of the system in case of either failure or mode change.

As far as mission management and control functions are concerned the corresponding software will operate as intelligent agents which fuse sensor information, monitor critical variables, generate optimized plans, alert crew to problems as they arise and recommend optimized solutions in real time. Response agents capture basic data, communication (forecast and other information) and apply optimization technology to generate new plans based on changed conditions and states. The crew can consider recommended plans in a "what if" manner, i.e. making changes to the agents suggestions or accepting new recommendations. Last, but not least, agents will offer learning capability and will be designed almost automatically in the future.

Among others the corresponding software will apply soft computing techniques for automatic data analysis in order to reduce complexity and subsequently to alleviate decision processes. Active decision support systems utilizing hyperknowledge and automatic reasoning techniques will synergetically complement and extent the users acquired knowledge management capabilities or even replace the human in autonomous systems in the far future.

Such advances will require new approaches to the generation, validation and certification of software and will involve major rethinking of system reliability, fault tolerance and assurance of function. By the year 2020 Computer Aided Software Engineering will yield reductions in software Life Cycle Costs. The software production will be easier and quicker and the final product quality will be much higher as compared to today.

1.4 High Speed Optical Switching and Networking

The availability of 100-1000 Gbit/s, 50 channel, high-speed-switchable optical data routing, dissemination and control technology is a critical enabling technology for air vehicle profile (radar cross section and drag reduction) and asset sharing. To minimize antenna surface area and maintain high performance sensing and surveillance capability on an air vehicle consistent with drag-reducing shape and low radar cross section involves using radar and other antennas and sensors of non-optimal shape and size and with inconvenient function sharing. This switching technology and the optical network which it supports are critical for ameliorating the non-optimal shape and size, and for enabling cost saving sharing of processing resources in the avionics. Optical switchable network links will also be used to connect different processing networks like e.g. sensor, signal and data processing networks. The technology, although deriving by telecommunications and PC-networking technology, will be in specialized areas

still driven by defence requirements. This capability is necessary to achieve "smart skin" vehicles.

1.5 Effects of the Technological Advances on Integrated System Structures and Functions

High performance integrated circuits will build high performance modules which will be packaged in racks and construct the integrated modular system of the future. The modules will have standardized interfaces and will be connected via a powerful network. The various module types will be shared by the software functions and have a shared redundancy. In case of failures the fault management software will automatically reconfigure the system to run on the reduced set of hardware modules. This may - in case of too many faulty modules in one class - result in graceful degradation of performance.

The software will be structured in layers. The lower level will handle the hardware specific characteristics of the modules and provide a hardware independent interface to the next higher level in order to enable the higher levels to be implemented independently of specific hardware. Next level will be an operating system that manages the parallel execution of software functions and safe separation. The operating system will have a standardized interface to the applications. Other standardized modules will handle system reconfiguration in case of faults or mode changes of the system.

The powerful optic switchable network links as mentioned before will connect the several racks of the system such as the sensor network and the signal processing network of the data processing network. Optical communications will also be deployed on-card and at card interfaces to reduce processing and data dissemination bottlenecks, and to reduce connector pin spacing.

Integrity of the system will be implemented by built-in hardware and software fault-tolerance together with fault detection mechanisms on all levels of hardware and software. High Integrity will be achieved by spatio-temporal redundant structures, providing the processing and monitoring of the data on different hardware and with data diversity in the software as well as by fault management software which will report the failure and perform safe automatic reconfiguration of the system.

High computing power will enable implementation of new powerful algorithmic, symbolic and sub-symbolic processing providing vastly improved quantity, quality and type of information provided.

Due to high performance communication links to airborne, space and ground elements in future Integrated Mission Systems, all available information will be combined into one picture. This will include results from simulations that predict the future situation ("look into the future"). The result will be a new quality of the full mission picture at every element of the system.

Integrated presentation of the information to the pilots and operators will evolve to enable quick assessment and reaction to the tactical situation. Limitations of the one-man-cockpit will be eliminated by support of ground staff or by totally remote operated vehicles ("telepresence").

Based on the optimized assessment of the situation both integrated and automated actions can be performed such as coordinated deployment of weapons, electronic countermeasures, radar operation and maneuvers.

Dependent on the status of the mission automatic reconfiguration of the mission system will be initiated to make optimal use of the resources. This will additionally happen in case of malfunctions of mission system elements. Automatic fault management functions will automatically handle the failure and restore safe operation of all functions.

2. Micro Device Technology

2.1 Potential

Beside the new IT the new Micro Device Technology (MT) is of particular importance. It will enable light weight, compact, adaptable modules, subsystems and systems (e.g. inertial sensors, electronic eye, micro radars, guided bullets) which, in a synergetic complementary combination with new IT, offer unprecedented performance with a low life cycle cost potential. Their implementation is based on advanced mircro-electromechanics, electronics and optics, silicon technology and evolving nanotechniques. Together with new materials, MT can be applied to build multifunctional smart structures. Waferscale integrated, redundant inertial systems will become feasible which can be integrated with miniaturized GPS and Focal Plane Array imaging micro-optical technologies. Device miniaturization will yield extreme low cost, weight and volume taking advantage from proven and rapidly further developing semiconductor type production. Built-in fault detection mechanisms inside modules and circuits will support reliability, maintainability and integrity of mission functions, systems, elements and subsystems.

As examples monolithic Microwave Integrated circuits (MMIC's) and active, adaptive optics shall be mentioned here and in section 3.

2.2 Monolithic Microwave Integrated Circuits

MMIC's based on gallium arsenide and silicon technology are of strategic importance for advanced microwave sensor developments such as active

arrays for radar and electronic warfare applications. They form also the basis for smart RF skins and future conformal arrays.

Further increasing system demands (e.g. very low noise figure, higher RF output power) and applications at ever higher frequencies leads to continual research and development in the semiconductor area. The well known semiconductors silicon (Si) and gallium-arsenide (GaAs) will be completed by new material compounds (e.g. SiGe, AlGaAs, InGaP).

A high potential for future applications is seen for the HEMT (High Electron Mobility Transistor). Beside of the well known applications for low noise amplifiers (up to nearly 40 GHz) this type of transistor will be used in future components up to 100 GHz.

Another high potential for future applications is seen for the HBT (Hetero-Bipolar Transistor), especially for high power applications and components with very low phase noise. The ongoing development of HBTs related to the transistor structure as well as to the semiconductor material (e.g. AlGaAs/GaAs) will lead to power components with very high efficiencies (> 50%) up to nearly 30 GHz.

The semiconductor materials, listed before, make partly possible the manufacturing of optoelectronic integrated circuits (OEICs). Therefore, super components will be realized to modulate RF signals (up to 30 GHz) on an optical carrier as well as to demodulate in the RF band in the future. This concept allows also the distribution of the required control signals.

Future circuits for microwave and millimeter wave range will be based on coplanar structures, multifunction circuits and multilayer structures.

With conventional technologies requirements such as wider bandwidth, improved frequency agility, multifunction capability and inertialess multi-target tracking often conflict. The use of MMICs is the assumption to realize active phased array antennas for Radar, SAR and ECM applications as well as related systems. Only this technology will make possible the realization of new system features (including multifunction and flexibility) at a low volume and a rational series price.

2.3 Active and Adaptive Optics

Active and Adaptive Optics refer to optical components, assemblies and systems whose performance is monitored and controlled so as to compensate for aberrations, static or dynamic perturbations such as thermal, mechanical and acoustical disturbances, or to adapt to changing conditions, needs or missions.

The biological visual system is an example of active and adaptive optics. The eye is capable of adapting to various conditions to improve its imaging quality. The active focus system of the eye-brain combination is a perfect example. The brain interprets an image, determines the correction necessary and applies that correction through biomechanical movement of the lens of the eye. This is closed-loop correction.

In engineering active and adaptive optics comprises all techniques and technologies (e.g. macro/micro optics, macro/micro mechanics, micro electronics, soft computing) to build optical systems that improve performance by dynamically and autonomously correcting for aberrations. In so doing, properties of the system such as image resolution or on-target power density are optimized. Three elements of the system accomplish this: a measuring device that senses the aberrations that the system must compensate for, a processor to convert this information into a usable signal, and a wavefront altering system to undo the damage from the aberrations (e.g. deformable mirror).

All imaging systems can benefit from this technology. To fully apply the potential, optical instead of electro-mechanical control techniques will become most useful. In combination with soft computing techniques active, adaptive optics can mimic biological eye-brain structures.

3. Multi-Functional Structures

New kinds of multi-functional structures are based on the ability of particular materials to change specific physical or chemical properties when required, and that in a controllable, reversible, stable and reproducible manner. So, structures with actuatory and sensory properties can be generated. In combination with new kinds of information-processing structures (cf. chapter 1), learning, adaptive basic components of multi-functional systems or of system elements can be realized.

As in biology, they have sensors (sense, nerves), control and regulating elements (brain) as well as actuators (muscles).

4. Biotechnology, Biocomputing

In a medium to long term perspective the next quantum leap in both IT and MT can be expected through the application of Biotechnology materials and processes e.g. natural materials for sensors, protein based computer. The latter will be fabricated from biological molecules with diode like features promising very compact size and fast data storage in 3-D memories as well as parallel processing in e.g. neural network structures. Based on the current research status a superchip with 10 billion bit memory capacity can be expected in the future.

However decades of further research are necessary, before a Biotechnology computer or corresponding computing elements will be available for operational use.

As far as the application of Biotechnology materials for sensors is concerned, first applications can be expected in the near future.

5. Benefits for the User

The new IT will yield computational and machine intelligence which offers the user the opportunity for cognitive automation of typical „recognition-act cycle“ activities on various functional and operational levels, e.g.:

- For reasons of human limitations in more demanding dynamic scenarios and in the operation of complex, highly integrated systems, there is the necessity for extended automation of functions on higher levels such as mission management and control.
- Furthermore the implementation of intelligent functions on lower levels such as the fusion and interpretation of sensor data, multifunctional use of sensor information and advanced nonlinear learning control become feasible.
- Improved effectiveness in diagnostics and maintenance of systems, sub-systems and modules will have a considerable effect on life cycle costs and reduce the number and qualification of personnel.

The high performance capabilities in sensor operation, signal/data processing and data fusion capabilities of future integrated Mission System will lead into much quicker detection and identification of targets and enable intelligent reaction including automatic assessment of all possible results of alternative actions. The optimal use of the active and passive sensor information (on and off board) will enable night and bad weather operations as well as silent force activity. Together with a high degree of automation the future Mission System will gain superiority in all situations.

Due to the high availability, reliability and integrity of the system users will gain more confidence in the mission success. Support by staff through tele-presence will additionally improve faith. Many operations will be performed with uninhabited combat aerial vehicles where the pilots do not even leave the country. These unmanned vehicles with Mach 12-15 performance will enable the Air Force to be anywhere in the world in minutes. Furthermore the unmanned hypersonic aircraft will cut costs dramatically and give better performance.

The introduction of integrated modular electronics on all Mission Systems Levels will definitely save cost. Reduced maintenance effort, reduced pre-mission operation and reduced training effort will reduce utilization cost. Even development and verification effort will shrink due to layered software standards and therefore higher reuse of software modules will be possible.

The concept of shared redundancy will provide major performance improvements by gaining higher availability and reliability of the functions. This leads to reduction of weight, volume, power requirements and finally lower procurement and maintenance cost for Integrated Mission Systems with considerably improved efficacy and efficiency.

In concluding it can be stated, that new technologies wisely and consequently integrated into systems are not only affordable but rather are the necessary key to a leap-type improvement of the yield/cost ratio.

6. Final Remarks

In summary it can be stated, that significant changes are currently taking place in the new IT and MT regarding functional capabilities, performance, characteristics and cost. These changes will influence the user and the supporting industries organisational structure. The rate of change and related realizations will exceed normal evolution and will have great social impacts accompanying the technological and functional advances. In order to accomodate this, the strategies of users and industry must be adapted accordingly.

Propulsion and Energetics Panel

Contents

Pulse Detonation Wave Engine

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Abstract

Tactical missiles based on Pulse Detonation Wave Engines (PDEs) have the potential of increased range, enhanced survivability, lower cost, and reduced time of flight. The advantages derive from two overall features of the intermittent combustion device compared to competing steady flow engines. The first feature is the quasi-constant volume characteristic of the detonative combustion process with theoretical increases of the specific impulse and the thermodynamic cycle efficiency. The second feature is related to a simple design which combines compression, combustion, and thrust production in one component. The paper discusses various missile applications of the detonation based cycle, several design issues, and R&D needs which have to be resolved to take full advantage of the PDE.

Vision

Achieve a propulsion system with higher thrust and Isp at lower weight, smaller size and reduced cost relative to more conventional steady flow systems.

The pulse detonation wave engine is a device that can provide more than a 30% increase in thermodynamic cycle efficiency compared to the constant pressure burn Brayton cycle. Experimental work conducted over the past five years has focused on the viability of this engine concept, and the results indicate the potential of achieving high performance over a wide operating range. Airbreathing and rocket modes of operation are possible providing the capability to self boost and carry out subsonic and supersonic missions while changing modes on demand.

Scope

The current interest is in the development of the detonation wave engine derived from two overall features of this intermittent combustion device. The first feature involves the improved propulsive performance attributable to the quasi-constant volume characteristic of the detonative combustion process increasing the useful energy available for thrust production. this leads to a theoretical increase in Isp of up to a factor of two compared with a ramjet, depending on the application (speed, etc.). Furthermore, the increase in thermodynamic cycle efficiency associated with the high rate of heat release of the detonation process, on the order of several thousand feet per second, also indicated a thrust-to-crossectional area significantly higher than competing systems. The second major feature of the pulse detonation wave engine is its construction in which compression, combustion and thrust production occur mainly in the detonation (combustion) chamber. The two features lead to compact, lower weight (higher thrust-to-weight) designs that are potentially simpler in construction than competing steady flow engines. These advantages apply at all speeds, subsonic and supersonic.

Military Need

The improved range, survivability, low cost (simplicity), and potential reduced time of flight features associated with the superior performance potential of pulse detonation wave engines, meet many military requirements for tactical missile systems. Consequently, a broad range of applications are possible using the full potential of this detonation based cycle. Table 1 summarizes a crossection of applications that include air launched, surface launched, Rocket Based Combined Cycle (RBCC), and pure rocket mode missions.

Critical Design Considerations

There are several design issues that must be adequately resolved to bring the pulse detonation wave engine to fruition at its fullest potential.

Inlets

Since a significant portion of the compression process is derived from the detonation wave in the combustor relatively low contraction ratio inlets are possible for air breathing pulse detonation wave engines. Normally, this corresponds to minimum losses in the inlet compression process. However, high quality flow with absolute minimum distortion should be delivered to the combustor to aid in achieving high quality planar Chapman-Jouguet detonations. Furthermore, to ensure that the inlet remains started during the intermittent operation of the engine, steady inlet flow with appropriate isolation and manifolding is required. This requires consideration of modular engine designs.

MISSION	PRIMARY OPERATING CHARACTERISTIC (S) REQUIRED	OPERATING MODE(S)
Standoff (cruise) Missiles	High Isp. Long range propulsion, air or surface launched	• Pure air breathing • Rocket mode in multimodel operation for boost, end-game maneuver and terminal acceleration for deeply buried targets.
Target and Surveillance	Compact, low weight, high performance	• Airbreathing and/or • Rocket
RPVs and UAVs	Lightweight, small or modular construction for large UAVs	• Airbreathing and/or • Rocket and air breathing
Air-to-Air Missiles	High Isp and thrust-to-weight, reduced propellant mass, high acceleration	• Rocket and • Mixed air breathing-rocket
RBCCs	Higher thrust-to-weight, higher Isp	• Multimodel rocket-to-air breathing pulse detonation operation-to-Scramjet • Split flowpath
ASAT, Strap-Ons and On-Orbit Maneuver	High Delta-V, launch augmentation and compact, low weight, high acceleration	• Rocket mode

Table 1: Mission Applications Using Pulse Detonation Wave Propulsion

Air Inlet Valves and Seals

Inlet air valves, when used, are part of the air induction system and must be designed to optimize the inherent valve losses through conversion of the associated turbulence to maximize fine scale mixing in the combustor while achieving the required large scale uniformity of the detonable mixture. Seals for inlet valves (as well as exhaust valves, when used) must also be considered.

Combustor

The combustor is the primary component in the pulse detonation wave engine. Adequate mixing (and vaporization when storable liquid hydrocarbons are used) must be made to occur very rapidly to achieve effective firing frequencies up to the order of 100 Hz. In addition, near direct detonation initiation and propagation must be made to occur reliably using devices whose weight and energy do not significantly impact system performance nor safety.

Other Design Considerations

Controls, guidance, airframe integration including a nozzle, and structural integrity, must also be considered in the design process.

Key Technology Development Requirements

The initial focus of a technology development effort should be on gaining an improved understanding of the flowpath physics carried out in parallel with the design of a ground and flight test demonstration activity. Current R&D in the US and France suggests that pulse detonation wave technology could be brought to fruition in the near-term through such an integrated effort. The areas addressed here summarize the basic needs with emphasis on operability and performance of a generic pulse detonation wave engine.

Engine Process Control

Several events in engine operation must occur in sufficiently short time increments enabling overall frequencies on the order of 100 Hz. At this rate, the chamber must be filled, detonated and scavenged in about 10 msec requiring that the following processes be made to occur at a sufficiently rapid rate:

a) Filling and mixture preparation through rapid fuel (and oxidizer) injection and micromixing. Adequate macro- and micro- mixing are needed to ensure high quality near planar Chapman-Jouguet detonations. However, the effect of non-uniformities is unknown and data is needed to establish the impact on detonation characteristics.

b) Direct detonation initiation is needed to ensure that maximum pressure is achieved for thrust generation. Currently, detonation initiation requirements are based on highly empirical relationships that need to be extended and validated in rapid fire, highly dynamic environments.

c) Rapid scavenging of combustion products. Although blowdown of the chamber under practical conditions will typically occur well within the 10 msec time duration. the state of the

residual products of combustion must be controlled to avoid premature ignition of the subsequent charge.

d) Control of fuel (and oxidizer) injection, inlet and exhaust valve timing, and detonation initiator timing. Timing of these events is critical to the operation and performance of this engine in terms of speed variation and guidance.

In addition to these issues, specific design features are also critical to the successful development of pulse detonation wave engines. For example, separated flows caused by adverse pressure gradients including shock-boundary layer interactions at high speeds and rapid area changes at all speeds must be avoided. Separated regions are characterized by residence times that are substantially longer than duct flow-through times. This means that products of combustion can be "trapped" in recirculating zones and act as ignition sites for the subsequent charge, causing premature ignition. Furthermore, surface temperatures and cooling requirements must be understood and controlled to avoid premature ignition and to define thermal-structural requirements.

Analysis and Test

Because of the numerous interactions of the flow in the pulse detonation wave engine, a purely empirical approach to its development is unlikely. However, it is a prime candidate for analysis and design by CFD methods. Therefore, a primary element of the development plan is the application of an hierarchy of CFD tools that range from an engineering level to a very detailed level to help understand the flowpath physics of pulse detonation wave engines. Experimental requirements will evolve from this effort.

The development effort should begin with a functional analysis that includes mission and application studies. This work will serve to identify roles for the pulse detonation wave engine including stand-off missiles (subsonic and supersonic), reconnaissance missions and target drones, etc. Furthermore, the functional analysis will also help to prioritize the technology requirements for focused applications. Concurrently, the CFD analysis hierarchy must be developed and include features required to treat components of the pulse detonation engine cycle. This should include fuel injection, mixing with oxidizer, detonation initiation and propagation, and scavenging. Experiments to reduce critical uncertainties including direct-connect, semi-free jet and free jet testing must be carried out and be followed by a sequence of flight demonstrations.

Controls

An integral element of a successful development process for the pulse detonation wave engine requires the design of a coherent control strategy for the sub-components and overall engine operation.

Summary

The superior performance potential of the detonation based cycle meets many future military requirements for tactical missiles, in particular the need for higher specific performance and more compact, lower weight designs. Airbreathing and rocket modes of operation are possible providing the capability to self boost for subsonic and supersonic missions. Current R&D efforts suggest that the PDE is a realistic propulsion alternative for low cost tactical missiles, however, several design issues have to be adequately resolved to bring the PDE to fruition at its fullest potential. These include air inlets, air inlet valves and seals, combustor to achieve effective firing frequencies up to the order of 100 Hs, and a coherent control strategy for the sub-components and overall engine operation.

Gun Technology for the 21st Century

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Abstract

Conventional solid propellant guns have been around from more than 600 years. While quite a number of significant advances in performance and safety have been realized over this period of time, gun developers are currently in a position where only minor improvements may be expected. In order to meet the need for increased velocity and lethality in the 21st Century, it is necessary to consider nonconventional gun systems. Among the systems currently being developed are electric energy guns and liquid propellant guns. While these gun systems offer several potential advantages over conventional systems, they also present many new technical challenges. This chapter gives a brief description of several developmental systems and the specific challenges that must be overcome before their potential for increased performance can be realized.

Introduction To Electric- And Liquid-Based Gun Propulsion

In the area of advanced gun systems, there are two principal areas of current interest: electric guns and liquid propellant guns. Of these systems, it appears that electric guns are the more likely to become a mature technology by the year 2020.

Electric gun systems (electromagnetic [EM] and electrothermal/electrothermal-chemical ET/ETC] systems) have the same basic objective (i.e., the acceleration of tactical projectiles to velocities greater than can be achieved with conventional propellants). The major limitation of electric systems is their need for compact, portable sources of large amounts of electrical energy. Currently available technology is insufficient to support the energy needs of these systems.

In general, electromagnetic rail guns function by means of a magnetic force on a moving current element (the armature). Depending on the type of armature used, the resulting rail gun can be placed into one of three categories: solid armature rail guns, plasma armature rail guns, and hybrid armature rail guns.

In the electrothermal category, there are at least two possible subsystems, i.e. pure electrothermal systems, which use only electric energy to heat propellant gases, and electrothermal-chemical systems, which use electrical energy to initiate chemical reactions that provide the bulk of the energy ultimately available to move a projectile. Both ET and ETC technology are considered to be "near term" since their hardware and interior ballistics are relatively similar to conventional systems. For this reason, ET and ETC systems are of interest to nations that currently produce conventional large-caliber artillery.

Interest in liquid propellant systems has historically been driven by the desire for a remotely operated weapon where the advantages of a liquid propellant could be effectively utilized. Among these advantages are: reduced facilitization and propellant costs; increased logistic efficiency and effectiveness; increased safety throughout the military system, including reduced vulnerability on the battlefield; simplified gun automation; and increased gun performance and effectiveness.

Of the possible configurations of liquid propellant guns, two designs have been foremost in interest: the bulk-loaded system and the regenerative system. Bulk-loaded systems, while mechanically simple, lack the ballistic control necessary for practical implementation. Regenerative systems, on the other hand, have demonstrated performance equal to that of conventional solid propellant systems through mechanical control of the interior ballistic process.

Electromagnetic Launchers

Electromagnetic guns fall into two basic classes: rail guns and coil guns. These differ in the geometry of achieving confined magnetic fields and coupling the resultant forces to achieve projectile acceleration as schematically shown in Figure 1 (following page). Compared to coil guns, rail guns are, as a rule, conceptually and geometrically simpler and have lower impedance (i.e., require higher current and lower voltage for a specific propulsion task). They have received far more developmental attention, despite the potential for greater energy efficiency from coil guns. Coil guns become more attractive at larger scales due to more efficient coupling and the difficulties associated with precise switching that may impose velocity limits lower than those for railguns.

Rail Launchers (Rail Guns)

For firing conventional munitions at conventional velocities, potential advantages of electric energy

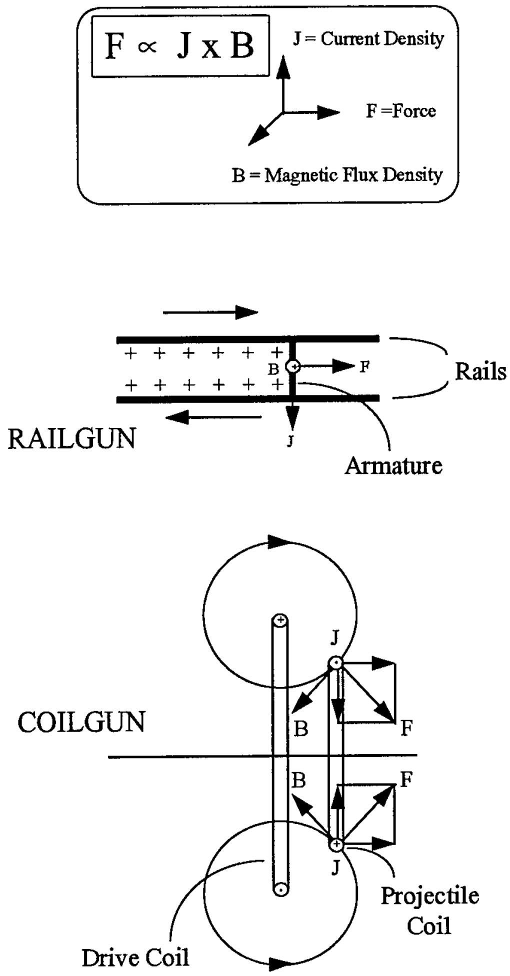

Figure 1: Generic geometries, magnetic fields, and forces in the rail gun and coil gun

weapons systems include improved survivability, decreased logistics burden, real-time adaptation of ballistic performance to the threat, extended munitions options and improved operational use, reduced maintenance cost, improved expected lifetime, and robotization.

For firing hypervelocity munitions, advantages of electric energy weapons systems include improved hit probability; new kenetic energy (KE) munitions concepts; improved conventional kill probability; enlarged engagement range; and multifunctional role in air, sea, and land combat.

Hypervelocity launch using rail launchers has been demonstrated by a large number of laboratory experiments. Gram size projectiles have been accelerated to velocities in excess of 7,000 m/s and new projectile designs of 1 kg have been accelerated to a velocity of 4,200 m/s. A standard armor-piercing fin-stabilized disgarding sabot (APFSDS) projectile, with a launch package mass of 3.55 kg has been successfully accelerated with a 90-mm bore, 7.5-m rail accelerator to a muzzle velocity of 1,985 m/s (Defense Research Agency [DRA], UK) at a launch efficiency, 0, of 0.27 (0 = ratio of the electromagnetic energy commutated into the accelerator and the KE at the muzzle). [Note: muzzle velocities for a "typical" 120-mm solid propellant gun is on the order of 1,600 to 1,700 m/sec.]

First steps to weaponization have been made. Large caliber rail accelerators (N 90-mm bore, 7-8 m, mass = 2.8 kg) have been designed and are being tested in the U.S.A. New materials (e.g., ceramics and ultra strong fibers) are being applied in these applications.

A complete medium-caliber (30-mm round-bore equivalent) rapid fire electromagnetic weapon system, including the pulsed power supply (total system mass is approximately 1,500 kg) has been designed and constructed (U.S.A.). Component tests are being pursued with launch experiments resulting in muzzle velocities up to 1,780 m/s and 0 of 0.35 for 180 g projectiles.

The primary challenge to successful fielding of an electromagnetic gun system is the need for compact energy storage and power supplies. For a typical ordnance muzzle velocity of 20 MJ, 60 - 80 MJ must be provided to the gun breech for each shot. This is a significant power requirement. For repetitive-firing weapons, energy storage and power supply requirements are even more demanding. To try to meet these demands, a considerable amount of effort has been and is being expended in the area of capacitors and rotating machines. While there have been many advances in capacitor technology, they have not been significant enough to expect an electromagnetic gun system to be fielded in the very near future.

Another challenge in the area of rail launchers is wear. Regardless of the type of armature used (solid, plasma, or hybrid), friction-limited velocity and concomitant rail wear are serious concerns. Of the three types of armature systems, wear is the least serious with the solid armature-based systems, which are characterized by a higher efficiency, and therefore by reduced wear. With further refinement, this technology may find a place in tactical warfare applications. Plasma-based armature systems suffer from poor efficiency at low velocity and experience significant resistive energy losses in the plasma. Hybrid armature-based systems make use of a solid metal main armature body with a thin layer of plasma that serves as an interface between the rail and the armature. The main obstacle for this technology is the problem of rail surface damage resulting from power dissipated in the plasma contact.

For military application of rail accelerators, an arc-erosion-free launch process followed by a

controllable transition behavior resulting in plasma boundary layers at the rail armature interface is required. For "transitioned armatures," which occur when there is an uncontrolled electrical arc between one or both armature faces and the adjacent rail, velocities as high as 1,200-1,400 m/s have been achieved (TNO, the Netherlands). Deposition of armature material and arc-erosion is unacceptable for repetitive operating rail guns. Research and development on the armature transition process is needed to proceed to fieldable rail guns, Moreover, improvement of the accelerator design with respect to weight per unit length must be made. Strong and lightweight materials will play an important role. Weight and size of pulsed power supplies and switching systems have to be reduced to make transportable electromagnetic rail systems possible. Together with compulsators, fast discharge bipolar batteries, pulse transformers, and SiC-based semiconductor opening switches look very promising to this end.

Linear Induction Launchers (Coil Guns)

The propelling force for induction launchers is created by the interaction of a current and a magnetic field. The primary advantage of these launchers is that current does not have to pass through a moving contact from the external structure to the armature. The main difference between these systems and rail guns is that the magnetic field for coil guns is generated by an applied driving current. For rail guns, the same current flows in the rail and the armature. The drawback for induction launchers is that they require a complex design of coils and power supplies as well as of control for synchronization of the coils. The requirement of extremely large power and rapidly increasing frequency have thus far proven to be an insurmountable hurdle for generators and for most power conditioners consisting of capacitor bank and switches. The issue of control of induced current distribution has also yet to be sufficiently addressed.

Among coil gun concepts, the coaxial traveling-wave launcher appears to be superior, in that it has uniform distribution of propelling and centering forces along the complete armature surface during acceleration, as opposed to aft pushing. In addition, there is no need for exact synchronization between projectile and drive coils. The main disadvantage of coaxial traveling-wave launchers is the cost of the required alternating current capacitors and switches.

Electrothermal Launchers

"Pure" Electrothermal Launchers

Pure ET guns use only electrical energy to heat propellant gases. These guns have energy requirements of the same order of magnitude as those of electromagnetic guns and, therefore, face similar challenges with respect to development of power supplies. Pure ET gun technology involves the use an inert propellant (e.g., water) whose only function is to provide a low molecular weight working fluid when heated to evaporation or decomposition. In general, it has been found that the energy required to evaporate the working fluid is so large as to make such gun systems nonweaponizable using near-term electric power technology.

Electrothermal-Chemical Launchers

The main advantage of ETC systems is that they can, with minor modifications, utilize existing gun hardware. They are often considered an "upgrade" technology because the gun tube and interior ballistics resemble those of conventional guns and because power supplies needed are approximately one order of magnitude smaller than for electromagnetic systems and, therefore, are more readily vehicle-integratable. They differ from pure ET systems in that inert propellants are replaced with energetic propellants. A shcmetic of such a system is shown in Figure 2. Compared to conventional powder systems, these guns offer increases in range (in excess of 50 km) and have the potential to deliver 140-mm performance from a 120-mm gun system. Increases in lethality, based on hypervelocity and novel projectile designs, are also possible. Challenges that remain to be addressed for these systems include demonstration of performance commensurate with conventional powder gun; identification of propellants with not only specific energy density superior to currently fielded formulations, but which also satisfy safety, insensitive munitions requirements, and manufacturing requirements; control of plasma/propellant combustion; and moderation of propellant temperature coefficient.

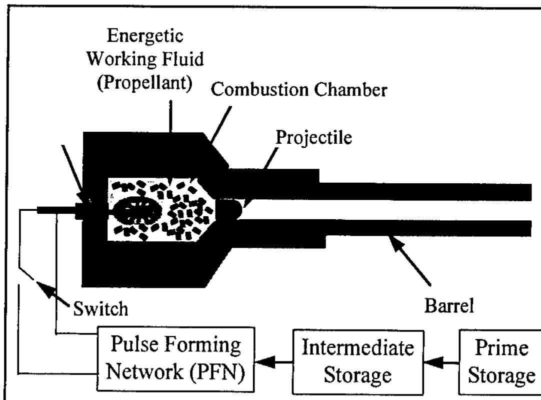

Figure 2: Schematic of an electrothermal -chemical gun

One current topic of research in the U.S. is the interior ballistic cycle of ETC guns. The goal is to identify potential mechanisms that may contribute to observed shortfalls in performance. Two main categories of mechanisms are of particular interest: those mechanisms in which energy, either from electrical or chemical sources, is bound in such a manner as not to be transformed into useful thermal energy during the ballistic cycle; and those mechanisms that result in changes in the hydrodynamics expected of a typical powder gun (e.g., the pressure gradient). Special attention is being paid to examination of plasma capillaries, which are considered to be critical elements in the conversion of electrical energy to thermal energy. Recent investigations of radiative losses by plasmas to chamber/gun walls has revealed that this should not be a serious concern.

Given the early stages of ETC research, it is difficult to make substantive statements regarding the characteristics of a system yet to be defined. This is also the case for electrical power supplies since so little is known about the sensitivity and vulnerability of existing components, much less the increased energy and power density components required in the future for tactical applications of electric guns.

With all its potential limitations and uncertainties, ETC propulsion continues to hold potential for substantial systems benefits. Existing data are inadequate to support rational projections of technology maturation. However, if current technical objectives of on-going programs in several nations are met over the next few years, development of an ETC gun during the first decade of the next century may well be possible.

Liquid-Propellant-Based Guns

The key technical and engineering challenges for the liquid propellant gun fall generally into gun and propellant categories. In the gun area, the presence of high-frequency pressure oscillations in the combustion gases is the key near-term technical challenge. These oscillations are not related to the lower frequency, longitudinal pressure waves that are responsible for breech blows in conventional solid propellant guns. The primary concern raised by the presence of these oscillations is their effect on sensitive projectile components (e.g., fuzes) rather than on the potential for combustion anomalies or gun damage. In the long term, the key developmental engineering challenge of the regenerative liquid propellant gun (RLPG) is reliability in the field environment. In the propellant area, the primary challenge is the engineering and design of the components and infrastructure that will facilitate successful integration of a liquid propellant into the field. These include not only production facilities, storage and transportation containers, handling equipment, etc., but also the new procedures and doctrine necessary to optimize operations with a liquid propellant. Emphasis must be given to systems design in order to exploit the reduced sensitivity characteristics of the liquid propellant (LP) and optimize safely and vulnerability reduction.

Bulk-loaded Liquid Propellant Guns

Although many problems have occurred in tests of bulk-loaded LP guns, the appeal of a LP charge continues and is based, in part, on the potential design flexibility of a liquid system that might be used for generating a variable charge for producing on command either a lethal or a nonlethal charge. Methods for controlling the combustion of bulk-loaded guns include three general approaches (i.e. the development of a repeatable functioning igniter, the use of chambergeometry for reducing instabilities associated with the gas-liquid interface, and multipoint ignition). In the U.S., the propellant of choice is XM46, a hydroxylammonium nitrate-based monopropellant that is relatively insensitive to various ignition stimuli.

Control of the early combustion is a necessary condition for avoiding an initially low gas generation rate, a problem that has been directly implicated in catastrophic failures of bulk-loaded LP guns. The other extreme, an initially high gas generation rate, can also result in problems associated with exciting large amplitude pressure waves.

The use of nonconventional chambers include two approaches: stepped chambers and multicelled chambers. The stepped-chambers approach shows that the volume of propellant adjacent to the igniter is an important control parameter that can be used for shaping the pressure-time curve. Based on modeling studies, the chamber steps located downstream of the igniter may introduce localized turbulence that promote a more rapid radial burn, thereby limiting the penetration of the initial gas cavity and, hence, the instabilities associated with gas-liquid mixing, a suspected source of variabilities in past bulk-loaded firings.

Regenerative Liquid Propellant Guns

A simple RLPG is depicted in Figure 3 (following page). It consists of a standard gun tube attached to a chamber that contains the regenerative piston. The head of the regenerative piston divides the chamber into two sections: a combustion chamber and a propellant reservoir. The length of the reservoir and, thus, the reservoir volume and maximum piston travel, are defined by a breech element through which the piston shaft extends. Cylindrical injector orifices are located in the head of the poston. These orifices are initially sealed to prevent leakage of the

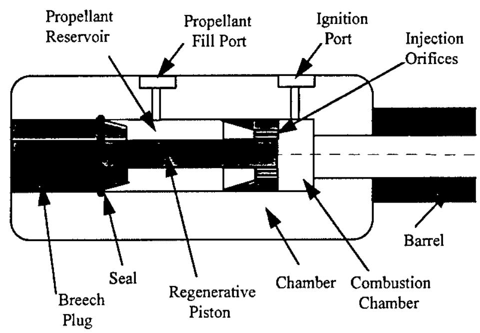

Figure 3: Schematic of a simple in-line regenerative test fixture.

propellant into the combustion before ignition. An ignition train (consisting of a primer, ignition charge and, in some cases, a booster charge) complete the system. Although recently the U.S. Army has shifted attention away from LP guns for its Advanced Field Artillery System due to schedule and cost considerations, there have been several notable accomplishments by that LP program, including a demonstration in ballistic repeatability approaching that of solid propellant guns, a demonstrated range firing in excess of 40 km, development of a predictive multidimensional model, rapid transfer of a LP from the reservoir to the combustion chamber at high mass flow rates, and the integration of all required support systems into a test hardstand. As in any development program, various problems were encountered and, in some cases, resulted in substantial damage to test hardware. Most problems fall into two general categories: operational and combustion.

Examples of operational problems in the U.S. include a reservoir to gun chamber leak resulting in a partial bulk-loaded firing and a pre-ignition of the charge during propellant transfer into the reservoir. The first example caused minimal damage to the gun. The test is of ballistic interest because of an abnormally high rate of pressure rise that resulted in a high performance firing with a constant pressure coefficient of 0.95. [Note: an ideal conversion of chemical energy to KE would give an exponent of 1.00.] The second example of an operational problem was an incident that resulted in damage to the gun and was caused by what is believed a material incompatibility problem. The propellant used in the 155-mm program is XM46, a hydroxylammonium nitrate based monopropellant. This propellant offers many safety advantages, however, its incompatibility with many materials, including transition metals, increased the system integration risk. During transfer, the propellant came in contact with a damaged transfer fill line where propellant was likely exposed to an incompatible material.

The second category of problems is related to combustion. Examples include the injection of propellant from a liquid propellant igniter that may result in large amplitude pressure spikes, and the hydrodynamic response of the propellant reservoir to the ignition and early combustion during start-up. The first example of a combustion-related problem involves the coupling between the hydrodynamics and combustion that may result in large amplitude pressure spikes. Based on multidimensional studies, this type of problem is believed to be associated with a local build-up of partially burned or unburned LP, especially during the early start-up. More effective dispersion of the injected propellant and better control of the propellant decomposition during start-up through the use of chemical additives are approaches that may avoid this problem. The second example of a combustion related problem is related to a compliant system that is not adequately damped, which may excite low-frequency pressure waves, especially during start-up. Some evidence suggests that these low frequencies may contribute to piston reversals. The LP program has formulated the guidelines for the successful development of an alternate propulsion gun system. Although various problems were encountered, the advances made during the program demonstrated the feasibility of a large scale gun where a liquid propellant could be transferred at high loading rates and successfully fire a projectile under remote operation and with controlled combustion. Designs based on advanced interior ballistic and finite element stress models were developed that could be used to support development of either future liquid propellant man-operated weapons or to support development of remotely fired weapons where the advantages of a liquid propellant could be effectively utilized.

Summary

To overcome the challenges facing both electromagnetic and electrothermal gun propellant systems, efforts in the area of compact energy storage and pulsed-power delivery must continue. For electromagnetic gun technology to reach maturation, resources must also be focused on concerns related to wear and to the containment of pulsed power supplies (in the event of failure).For successful fielding of a liquid propellant gun system, additional research in the area of ballistic control and liquid propellant service life must be pursued. In view of the challenges faced by all three major gun propulsion technologies, it appears that the electrothermal chemical should be regarded as the most likely near-term option of the three gun system candidates.

Laser Power Beaming: An Emerging New Technology For Power And Propulsion In Space

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Abstract

The potential of laser power beaming from a ground-based laser to satellites is discussed. The laser power may be used for propulsion and to increase the electric power available from the satellite. The increase relative to solar power generation can be an order of magnitude using the same size solar panels. For propulsion, it is proposed to beam the laser power through the atmosphere to a "tug satellite" which carries launched satellites to a higher orbit. The increased satellite electric power may be used to provide surge power to inhibit jamming of satellites in wartime, to overcome the increased atmospheric absorption in microwave operations, to provide orbit changes or corrections, to extend station keeping and satellite lifetime, and to transport malfunctioning satellites to the Space Station for repair and reinsertion in orbit. Key elements in the proposed concept include a 100 to 200 kW free-electron laser, a 3 km long underground ultra-high vacuum tube and a novel adaptive optic telescope. All elements in the concept have either be demonstrated or prototyped.

Introduction

The technology for putting satellites into orbit and keeping them operational is an important consideration for the 21st century. Satellites in space are a key to military communications, surveillance and navigation. At present there are severe limitations to how much power is available for use in space and on orbit correction, lifetime extension and moving or repairing satellites, particularly those in high earth orbit beyond reach of the Space Shuttle. This paper deals with laser power beaming to satellites and the conditions under which those limitations may be relaxed using this novel technique.

It may be helpful to enumerate briefly why satellites are so important. They provide the backbone of almost all of our modern communication technology. They are crucial to long distance radio, television (video communications), and telephone (long distance as well as cellular phones). Cellular telephones will be more and more widely used for both civilian and military applications. In the future they will have better and better coverage (no blind spots where communication is impaired or impossible) as more satellites are placed overhead. About 75% of U.S. military communications overseas are handled by satellite and 90% of communications to the U.S. Navy fleet are handled by satellite (Ref. 2).

In addition, satellites are key to both battlefield surveillance and to monitoring hostile or friendly activities worldwide. Solar power is now the only power source available to operate satellite surveillance systems. If additional power were available, an all-weather battlefield radar surveillance net could be mounted. During the cold war the Russians spent millions of rubles trying unsuccessfully to develop a satellite nuclear power capability for an all-weather radar satellite surveillance system. The alternative to that power source is laser power beaming, the subject of this paper.

Another function of satellite surveillance both in a battlefield and elsewhere is weather prediction and analysis. Weather satellites provide vital information that indicate rain, snow, cloud cover and expected wind direction and aids in predicting hail, hurricanes, tornadoes, and perhaps wind shear conditions. In wartime such information can be vital.

Global Positioning System (GPS) satellites currently provide two accuracy systems, one for commercial and one for military use. The system accuracy for personal hand-held or built-in GPS receivers for private and commercial aircraft, private power and sail boats, ships at sea, hikers, bicyclists, and automobiles is on the order of a few yards. They may even be useful for evaluation of the earth platelet movements leading to the prediction of earthquakes. This dual use program is a good example of how civilian uses can help to underwrite military system costs. The price of personal hand-held commercial systems that are available is as low as a few hundred dollars. These types of receivers were widely used in the Gulf War.

The military have a more accurate coded operational system. The many military uses of GPS position sensing include aircraft and ground navigation, accurate determination of friendly troop locations, and locations for real-time surveillance video of battlefields day or night from unmanned aircraft vehicles (UAV). Ships at sea, landing craft and other

navy vessels can use GPS as well as battle tanks, jeeps, forward air strike directors, etc.

There are some uniquely military satellite problems which are not duplicated in the civilian sector but to which laser power beaming can make a contribution. Examples are moving geostationary satellites in orbit over a battlefield; providing boost power for ship navigation, aircraft and missile systems using GPS; and obtaining high resolution images of space objects.

Two factors dominate all other space development issues, namely (1) the cost of space transportation and logistics, and (2) the availability of operating power. Since the cost per pound of putting anything into high orbit is very large (presently about $72,000/lb. to geostationary orbit), the level of commercial and government utilization of high earth orbits is significantly constrained. Launch costs for a satellite to geosynchronous orbit are typically $80 to $100 million or more. Moreover, since power generation and storage systems are relatively heavy and thus very costly, the magnitude of all activities in space is further constrained by shortage of power. Large satellites always seem to be power starved. Figure 1 illustrates the power usage of a typical commercial satellite family as a function of the time at which they were placed into service. The most recent satellites in this series utilize twice the power of the highest point plotted. However, if we accept the idea that solar panel size has for all practical purposes peaked out, this exponential growth cannot continue unless a new idea is developed for supplying the necessary power.

Laser Power Beaming

Laser power beaming may be the answer both for propulsion and for supplying the additional power needed to operate future satellites once they are in

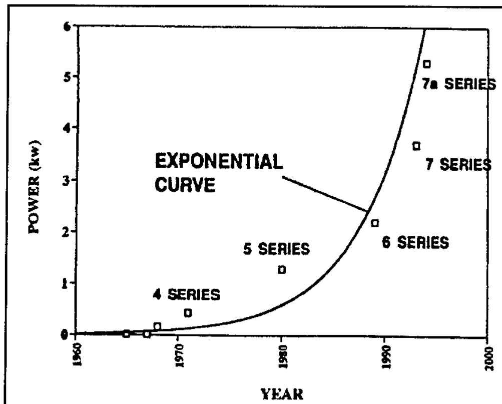


Figure 1 INTELSAT Telecommunication Satellite Power Growth

orbit. To supply propulsion, laser power is beamed through the atmosphere to a "tug satellite" which carries the just launched satellite to higher orbit. In this way, carrying up large amounts of fuel into space to supply the thrust for this operation is avoided. Once in orbit the laser provides the power needed to operate the satellite.

Today's satellite batteries are powered by photo-electric solar panels that convert sunlight into the electricity needed for satellite operation. If we assume that the panels have reached their maximum functional size, a tug, which would operate best with a much larger amount of energy than present solar panels operated in the usual way can supply, is possible but not very attractive. However, additional efficiencies are possible in the solar panel area. The silicon battery cells used by most satellites convert 13% or less of the sun's energy into electricity (Ref. 3) and the more expensive, less frequently used gallium arsenide cells convert 18.5% of the sun's energy(Ref. 4). By choosing a laser wavelength to increase the efficiency of photoelectric generation within the cell and also by increasing the power density on the cell, laser power beaming will provide over ten times as much electrical power to a satellite as the sun without overheating the satellite solar panels (Ref. 5). Laser power beaming thus provides a means for both increasing the power available for satellite operation and for efficiently using an inductive thruster ion engine instead of a rocket engine to provide the propulsion for sending a satellite from low earth to high earth or geosynchronous orbit at significant reduction in cost.

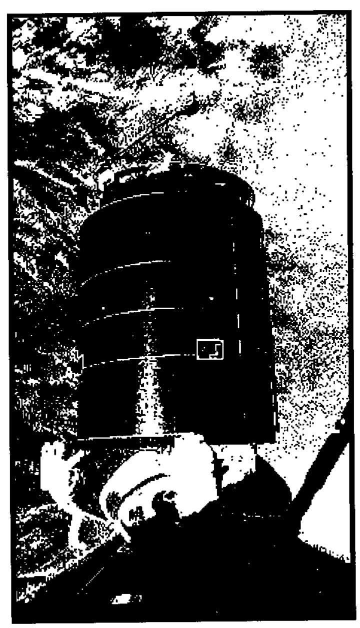
The National Aeronautics and Space Administration (NASA) name for this laser power beaming concept is Space Laser Energy (SELENE). Selene was the Greek goddess of the moon, and the concept may ultimately be the key technology needed to power a moon station. NASA studies conclude (Ref. 6) that launch costs to geosynchronous orbit could be reduced by a factor of three by using a space tug and SELENE. The light energy beamed from the ground, where power is cheap, is converted into electrical energy in space and used to power the inductive thruster on a "space tug" satellite. That satellite will make a rendezvous with a satellite which has been launched into low earth orbit and tow it into the desired higher orbit using power from the inductive thruster engines. The tug may also move a satellite in geostationary orbit from place to place over the earth. Such rendezvous techniques were demonstrated by the Space Shuttle when it rescued the malfunctioning INTELSAT 6 in low earth orbit, corrected its second stage rocket and successfully sent it into geosynchronous orbit in 1992. Figure 2 (following page) shows the INTELSAT 6 at the rendezvous site and the astronauts preparing it for relaunch.

Satellites in geostationary orbit could also be moved quickly and relatively inexpensively to another site using the tug. Such moves, which are of special interest to the military, are now very expensive. One satellite moved over the Persian Gulf during the Gulf war took several months to position and cost tens of millions of dollars. Since the earth is not quite round a satellite in geostationary orbit does not remain stationary relative to the earth by itself. Geostationary satellites are supplied with station-keeping rockets which are periodically fired in a controlled manner to keep the satellite stationary. To make the transfer to a position over the Persian Gulf, the geostationary satellite used its station-keeping rockets to propel itself, thus significantly shortening the satellite's effective life in space. Once the fuel for the station-keeping rockets is exhausted, the satellite must be abandoned and a new one must be launched. At present there is not way to move a satellite in high earth orbit except by using the satellite's own rockets. By using laser power beaming the satellite could have been moved quickly and relatively inexpensively. In addition, laser-powered station-keeping thrusters can be used on new satellites in place of the heavy rocket thrusters, increasing the expected life of the satellite in orbit or reducing its weight significantly.

Some mass, in the form of a gas, must be carried up into space even if laser power beaming is used. However, the thrust per unit mass of fuel is much greater if laser power beaming is used. However, the thrust per unit mass of fuel is much greater if laser power beaming is used than for a conventional rocket. Unlike conventional ion thrusters, which often use a heated filament, enough mass of ionized gas is ejected to produce significant total thrust. In operation, the laser beam irradiates the solar panel, generating approximately ten times the electrical charge obtainable over the same period from the sun. A capacitor is charged, which discharges through an inductive coil and ionizes the small amount of gas fed above the coil. The ionized gas is ejected producing the thrust. The parameter I_{SP}, which is a measure of the relative thrust per unit mass, is about 2500 as compared to 480 for a conventional rocket (Ref. 7). This factor of 5.2 explains why a lower mass of fuel must be carried than if a rocket were used for station-keeping or, alternately, why with the same mass of fuel the lifetime of the system is significantly extended. There are several variants to this idea, at least one of which is now commercially available for space applications.

The SELENE program calls for an array of six ground stations that would provide nearly complete global coverage to space (Ref. 7). This means that at any given time, a particular satellite will be in the line of sight of one or more of the laser ground stations and could therefore receive power from the earth. A prototype station is to be installed in the mountains near China Lake, California. This site is believed to be the best place in the continental United States for such a system (Ref. 8). This unpopulated area is close enough to the equator to reach most of the geosynchronous satellites over the United States, has the most cloudless days (260/year) of anywhere in the country (in 1993 when the clouds were

- **WEIGHT 2650 KG (MAX 4170)**
- **PAYLOAD 500 KG (MAX 662)**
- **INITIAL OUTPUT POWER 3500 W**
- **SOLAR AREA 12 M^2**
- **BATTERY AMP HRS 19-200**
- **DESIGN LIFE 12 YRS**
- **LAUNCH ATLAS, ARIANE, PROTON, TITAN, SHUTTLE**



CAPTURE OF INTELSAT 6 BY SHUTTLE 1992

Figure 2 INTELSAT Communications Satellite Ready for Relaunch into Geosynchronous Orbit

monitored continuously at the site there were only five completely overcast days all year), is centered in one of the largest restricted overflight areas in the country, has visibility which is often over 100 miles and astronomical seeing which is world class, has the largest geothermal electric power plant in the country nearby as well as a large coal-fired electric power plant with surplus capacity, and has plentiful water for cooling from wells in the China Lake playa or from reprocessed water which could be piped from the City of Ridgecrest. Ridgecrest, a highly technical community supporting the largest research, development and testing facility in the Navy, has a population of about 30,000 and is 45 minutes by air from Los Angeles International Airport.

The proposed SELENE system, shown in Figure 3, consists of:

1. A 100 - 200 kW free-electron laser providing reliable high power operation at significantly reduced cost;
2. An underground vacuum tube perhaps 3 km long that allows the tiny 1 mm diameter high quality beam at the output of the laser to expand by diffraction to a beam diameter of about 3 m, which can then be handled by conventional optics;
3. The novel adaptive optic telescope design with a 12-meter diameter multi-element primary mirror to project the laser beam into space;
4. The satellite, which contains a beacon allowing the adaptive optic telescope to sense the returning wavefront and correct the outgoing beam for atmospheric distortion.

A prototype of the free electron laser is now under construction in Novosibirsk, Russia, and is scheduled for completion in 1998. Parts for the China Lake laser will be sent from Novosibirsk to the Lawrence Berkeley Laboratory and assembled into a laser, then reassembled at the China Lake site. This laser will be completed five years from the date of program initiation. It will be coupled to an adaptive-optic telescope used to transmit the laser beam. The satellite could be outfitted with a low-power diode laser beacon mounted in front of the satellite to compensate for the change in isoplanatic angle. It would send a pilot beam to the ground station. Alternately an artificial guide star could be used to perform the atmospheric compensation. A wavefront analyzer at the telescope will derive information to correct the outgoing laser beam based on the incoming signal from the satellite laser or guide star. Any wavefront aberrations introduced by the atmosphere will be sensed and canceled as the output free electron laser beam traverses back through the same atmospheric path traversed by the light from the diode laser or guide star. Sampling rate will be between one and ten millisecond since the shortest time constant of atmospheric distortion is of this order. The laser beam will thus arrive at the satellite with minimal distortion. This concept was demonstrated in an experiment (Ref. 7) conducted at Mount Haleakala in Hawaii in 1990. The target satellite carried a beacon. Light from this beacon was detected and analyzed at millisecond intervals. The wavefront of the outgoing beam was then distorted in such a way as to exactly cancel the distortion

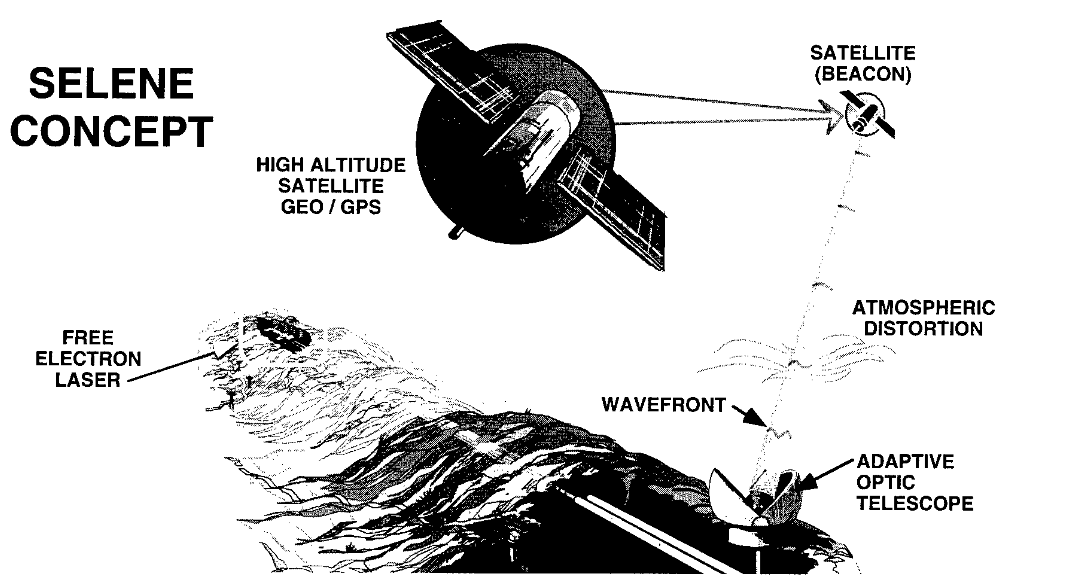


Figure 3 Laser Power Beaming Facility - SELENE System Concept

introduced by the atmosphere as the beam went up to the satellite. The demonstrated ability to perform this cancellation is a key to the success of SELENE.

In order to effectively beam laser power into space to power satellites in mid or high earth orbit, very large mirrors (perhaps 12 m in diameter or more) and an adaptive optic system to penetrate the atmosphere are required. Primary mirrors with adaptive optic segment sizes less than the equivalent Fried coefficient for atmospheric turbulence (typically 3-5 cm at zenith in the visible for normal sites, 20 cm or more for excellent sites) are optimum for atmospheric penetration. These new mirrors may have over one hundred thousand segments, each with its own computer driven adjustments. The idea has been described as a marriage of optics and Silicon Valley. The computational problem that this approach generates is believed to be solved (Ref. 9). Large mirrors composed of phased segments only a few cm in diameter are a new concept in optics. They offer the possibility of beaming laser power to space with minimum atmospheric distortion using relatively inexpensive very large mirrors. Such mirrors would have light-gathering power nearly 20 times greater than the Hubble space telescope. NASA has been investigating such mirrors since 1991 and has built a small operating prototype at Marshall Space Flight Center (Reference 10). Since they will be quite light., the mirror mount designs used for the Layton radio telescope designed at California Institute of Technology will be used for the completed mirror. An alternate design was developed during the Cold War and was successfully used to beam power to a satellite (Ref. 10) from San Diego, California, a most difficult site. These new classes of optics offer new possibilities in astronomy and may change the way we look at telescopes for space.

Summary

The potential of laser power beaming furnishing power and propulsion in space for military as well as civilian applications is very attractive. It is an ideal dual use program. Advantages are:

1. Launch costs to geosynchronous orbit can be cut to less that one third of present values;
2. Satellites can be moved quickly and inexpensively from one position to another without reducing their life expectancy;
3. Errors in orbit can be corrected without abandoning the satellite;
4. If the satellite malfunctions it can be repaired in space;
5. Aging satellites can be given a life extension by power beaming additional energy to them to supplement what they can receive from the sun;
6. On demand output power boosts of an order of magnitude can be obtained for GPS or other satellites which are being jammed by adversaries. (This objective is achieved by laser beaming additional power for temporary storage on the satellites to be released on call even when the satellite is on the other side of the world.)

Although the cost of setting up a laser power beaming system is fairly large, about $2B for the complete 6 site system, and some development work on the components is still required, the potential returns on investment make it both an attractive business and an attractive government venture. The implications for control of space in wartime by NATO security forces are significant, particularly if the development were done in a non-NATO country, and should be considered seriously.

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Structures and Materials Panel

Contents

Introduction

G.A.O. Davies

The Structures & Materials Panel of AGARD was asked to prepare a submission for the main volume (2) of the "Aerospace 2020" forward look. It was also suggested that a main theme of the S & M panel would appropriately be "affordability" or the technical advances that would take place and lead to reductions in both acquisition first-cost, and also in the total life cycle costs after delivery.

The S & M panel's report was eventually produced and found its way into the main volume "Perspectives for Aeronautical Technology in the Service of the Alliance", Volume 2, or in its appendices. One of the main conclusions in the report was that, although costs may dominate future defence procurements, the influence of S & M was not as great as equipment, weapons, avionics and systems, and software. Indeed in the total life-cycle costs the original base cost of materials was almost negligible, and so a very expensive material could pay off later if it was damage-tolerant or maintenance-free. However, although the ratio of acquisition to in-service costs is about 20-25%, the first cost has to be reasonable before customer's budgets can afford it. It was concluded that the design and manufacturing of the airframe structure or engine, was a significant cost-cutting opportunity.

The in-service costs represent a challenge to both advanced materials and structures, in reducing wear and tear, corrosion, fatigue, and the increasing use of sophisticated non-destructive evaluation and smart health-and-monitoring systems. This aspect will increase in importance as financial pressures lead to airframes and engines being kept in-service much longer than planned.

Volume 2 has been kept to manageable proportions; with the result that many important topics received only a brief mention. It was therefore convenient to be able to refer to this volume for further detail and emphasis.

The first article is an overview of the gains to be made by research and development in structures and materials, and the strategies needed by Government and Industry to foster this research. Not surprisingly the current trends appear all to be short term, with few opportunities to develop innovative solutions with a long term deliverable. One encouraging feature is the growing number of alliances, national and international, which avoids duplication in R & D, at least in the pre-competitive stage.

There follows three articles indicating where cost savings are going to accrue during the design and manufacturing stage. Integrated concurrent design is already becoming part of the whole virtual prototype and manufacturing process. The emphasis on low cost manufacturing inevitably turns to advanced composites where the cost is high but so is the potential performance.

The maintenance-free aircraft and the growing problem of ageing aircraft and engines are addressed in three separate articles, and finally an article on smart structures and materials summarises the potential for active control of aeroelastic and aerodynamic performance, and the further developments we can expect in health and usage monitoring systems.

Required R & D in Airframe Structures and Materials for Combat Aircraft

James J. Olsen

Abstract

This paper compiles and interprets requirements from several sources in the United States for Required R&D in Airframe Structures and Materials for Combat Aircraft.

The paper covers:

- The processes of developing requirements;
- Previous studies, sources of the requirements;
- Required R&D;
- Some ideas on collaboration within the laboratories, aerospace industry and possibly NATO.

Contents

1. Processes of Developing Requirements for R&D

Many of the following requirements for R&D in structures and materials arise from a knowledge of the immediate problems of and potential upgrades to the current fleet(s), combined with an estimate of future military aeronautical missions, aircraft to meet those missions and their potentially unique requirements for technology.

It is very difficult to establish requirements for long term R&D. The number of potential missions, aircraft and requirements for R&D are overwhelming to the technical leader who must allocate research personnel, funding and facilities. The directions from the higher levels of government and industry often are conflicting, vague or rapidly changing. There is an urgent need for a mechanism to provide a stable, long term view of the requirements for and potential improvements from new technology. There are at least four fundamental problems in the current processes of developing requirements for R&D.

1.1 Uncertain Future

Our views of the needs for technology usually are dominated by the problems in the current fleet(s) and our limited knowledge of the recent developments in science and technology. We are unable to know the unknown and find it unsettling to pretend confidence in our predictions of the future. Hence, there always will be an element of risk and uncertainty. We have a choice between being too cautious (continuing last year's program) or being perceived as having more "losers" in our technology programs than "winners".

1.2 Secrecy

Requirements of national defence may require that some of the newest and most influential requirements (e.g. stealth, enhanced weapons ...) by highly classified and closely held. As a result the requirements do not get to the "mainstream" R&D organisations and universities, and they may not play a strong role in the early years when their leverage could be greatest. The technology itself may play an overwhelming (and locally unknown) role in vehicle design and shift the former evolutionary relationships among the other technologies. The "compartmented" nature of the available knowledge may allow for considerably (possible unnecessary) duplication of effort, within both the classified and unclassified communities.

1.3 "Users"

Many of the views of the "Operators" are unbalanced toward the near term requirements and short term solutions. They usually are developed by currently serving officers in the operational commands who may have a limited knowledge of science and engineering and a relatively short tenure at their station. Consequently, their views of the "possible" and their long term vision are limited. Theoretically, those operational needs are fed back to the "Development Planners", interpreted by them in terms of requirements of current and future weapon systems, fed back to the "Laboratories" and then to the bench scientists. However, the administrative burden is large and complex, and the timescale of the process itself is on the same order as the timescale of the turnover and variability in the input data. Hence, it is very difficult to point to conclusive evidence that the process is timely and cost-effective and produces cogent guidance to the Laboratories.

1.4 Instability

While new military aircraft may take up to 15 years to develop, the plans at the top levels of government and industry for development of future aircraft seem to be in continuous turmoil - the syndrome of "What's in Aviation Week this week". As a result, the views on the relative importance of potential new aircraft may vary among organisations and among various functions in the aeronautical R&D community (design, aerodynamics, controls, materials, structure, manufacturing.... etc.). It is not an effective policy to frequently change the "guidance" to R&D scientists and engineers. Hence the process needs a stabilising force that still drives the technology toward the (usually) correct directions, while not sacrificing the technology base or the ability to respond to urgent requirements from higher authorities.

In Section 6, Conclusions and Recommendations, we make some suggestions and comments on recent efforts among the government and industry to restore a stable, long term view of the requirements and to foster effective collaboration.

2. Previous Studies, Sources of Requirements

Since World War II, there have been many studies in the United States which have attempted to determine the future needs and opportunities for military technology, particularly for aeronautics and space. Some of the early studies are summarised by Smith(1) and the National Research Council (NRC)(2). Among those particularly relevant to the United States Air Force (USAF) have been:

- Forecast 1;
- Forecast 11;
- New World Vistas;
- DOD integration Programs;
- Noor and Venneri;
- Paul et al.

2.1 Forecast 1

Forecast 1 was conducted by the USAF and US industry in 1962, attempted to anticipate aerospace "Technology Pushes" for the next 10 years. Among the technologies and weapon systems required were: composite materials, high bypass turbo-fan engines, enhanced radiation weapons, advanced (behind the B-70) piloted supersonic bombers and reusable space launch vehicles.

2.2 Forecast 11

Forecast 11 was conducted (primarily) by the USAF in 1985, addressed the potential requirements and advantages of a new set of technologies and weapon systems. Among them were: sparse arrays of space-based radar's, very high altitude (90,000 ft +) long endurance reconnaissance aircraft, autonomous weapons, "smart" cockpits, engines that take advantage of higher temperature materials, holographically simulated battle management, photonics, robotics telepresence, high power microwave weapons and combined avionics/airframes (smart skins).

2.3 USAF Mission Area Plans

Over the last several years the USAF has created Mission Area Plans for each of its five major operational commands:

- Air Combat;
- Air Mobility;
- Special Operations;
- Education and Training;
- Space.

Those requirements are fed to the USAF "Development Planners" through Technology Program Integrated Product Teams (TPIPTs) and into Wright Laboratory through Customer Focused Integrated Product Teams (CFIPTs). Those MAP/TPIPT/CFIPTs describe general requirements for technology for current and anticipated near term aircraft. Those requirements then are reflected in the USAF Laboratories "Technology Area Plans (TAPs)", for example the TAP for flight vehicles(3). Generally speaking, the TAP for flight vehicles shows the Laboratory's approach to meeting the requirements of current and anticipated weapon systems for improvements in:

- Cost;

- Readiness, combat availability;
- Survivability, observability;
- Weapons accuracy;
- Aerodynamic performance, manoeuvrability;
- Weight;
- Buffet, vibrations;
- Reliability, longer airframe life, longer economic service life;
- Inspection intervals;
- Field repairs.

2.4 New World Vistas

Among the more recent (1995) studies by the USAF Scientific Advisory Board(4). New World Vistas was composed of several Panels. Among them were a Panel on Materials and a Panel on Aircraft and Propulsion.

2.4.1 Panels on Materials

Divided its requirements into near term and far term opportunities. The near term (within 20 years) requirements reflected the needs of current and (currently) envisioned weapon systems, problems and technologies. They were related to:

- Airframe Structures;
- Aircraft Engines;
- Fuels and Lubricants;
- Optics and Electronics;
- Ageing Systems;
- Prevention of Pollution;
- Space;
- Transition of Materials into Flight Systems;
- Rocket Propellants;
- Energy Generation and Storage;
- Pyrotechnics;
- Explosives.

The far term section did not address "requirements", as such. Rather it contained very imaginative proposals for revolutionary improvements in weapon systems that might be achievable by continued research in materials.

2.4.2 Panel on Aircraft and Propulsion

Is the closest Panel to the topic of its paper, systematically considered the military aeronautical missions of:

- Air Mobility;
- Strike;
- Air Superiority;
- Long Range Bombing;
- Recce/Intel;
- Special Operations;
- Access to Space and Support of Space Operations.

They evaluated those missions and noted specific needs of each for the required attributes of potential weapon systems - including affordability, survivability, speed, range, lethality and flexibility. To assist in developing the needs for technology to satisfy the military aeronautical missions, the Panel then postulated several notional families of fixed-wing, aeronautical vehicles:

- Large Long-Range Aircraft;
- Uninhabited Aircraft;
- Special Operations Aircraft;
- Long-Endurance Aircraft;
- Modular Vehicles;
- Hypersonic Vehicles.

They did not consider trainer aircraft of their connections to the general aviation industry.

2.5 DOD "Integration" Programs

There currently are (at least) six other DOD/industry/NASA/University studies that attempt to organise the individual mission requirements, potential classes of aircraft and related technologies of the USAF, Navy, NASA, industry and universities - all under the guidance of the Office of the Secretary of Defence (OSD). They are:

- Integrated High Performance Turbine Engine Technology (HPTET);
- Integrated High Payoff Rocket Propulsion Technology (HPRPT);
- Fixed Wing Vehicle (FWV) Technology Development Approach (TDA)(5);
- Tactical Missiles;
- Avionics;
- Rotorcraft.

Some of these studies are mature (HPTET, Rotorcraft), and R&D programs are well underway; some have reached the stage of creating programs (IHPRPT); some are about to define programs (FWV/TDA) and others (Tactical Missiles, Avionics) are in planning.

2.5.1 FWV/TDA

Particularly relevant to this paper is FWV/TDA. This evolving DOD/Industry program postulated (in March 1995) the following classes of airframe technologies and subsystems:

- Aerodynamics;
- Flight Control;

- Structures;
- Aeronautical Subsystems;
- Maritime-unique Subsystems;

and families of vehicles:

- Fighter/Attack;
- Airlift/Patrol;
- Bomber;
- Special Operations;
- High Speed.

FWV/TDA established baseline aircraft and formulated near term (2000.2005,2010) "subarea goals", aircraft payoffs and technology objectives to achieve substantial improvements in mission capabilities.

For instance, in the mission area of fighter/attack, FWV/TDA established the baseline class of aircraft as being represented by the F-18E/F and the F-22. To obtain an "aircraft payoff" of a 25% increase in mission range would require the achievement of "subarea goals" such as a 10% increase in cruise L/D and a 20% reduction in the ratio of structural weight to gross takeoff weight. That in turn would require a variety of science and technology programs that achieved quantitative "technical objectives" in topics such as aircraft cruise drag, weapon drag, inlet duct length, structural weight, subsystems weight and volume, optimal control gains and active/adaptive aeroelastic lifting surfaces.

FWV/TDA is in the process (Sept 1996) of defining the necessary government, industry and university programs to achieve the technology objectives.

2.6 Noor and Venneri

In 1993-1994 Noor and Venneri(6) created a team of international experts from government, industry and academia and edited a masterful six-volume monograph on potential future aeronautical systems (civil and military) and on future materials, structures and structural dynamics technologies. The six volumes covered.:

- New and Projected Aeronautical and Space Systems, Design Concepts, Loads;
- Advanced metallic, metal matrix and polymer matrix composites;
- Ceramics and ceramic matrix composites;
- Tribological materials and NDE;
- Structural dynamics and aeroelasticity;
- Computational structures.

2.7 Paul et al

In 1996 Paul et at(7) summarised the evolution of military aircraft structures technology, including perspectives and requirements for the future. They discussed the history of:

- Materials;
- Structural Concepts;
- Design Criteria;
- Analysis and Design Techniques;

and projected the future for:

- Affordable Composite Structures;
- Smart Structures;
- Design using Virtual Reality.

3. Some Helpful Distinctions

3.1 Classes of Missions and Vehicles

For this paper we attempt to follow some of the above classifications with respect to missions and aircraft. We select representative missions and include a list of fixed-wing aircraft that include:

- The current fleet;
- Aircraft in some stage of development;
- A current view of potential future aircraft.

The idea is that the missions should represent the entire range of USAF aeronautical missions, and the real and "notional" aircraft should be adequate to excite the need for the full range of required technologies. We do not consider purely space missions (Boosters, Satellites,... etc). The missions and aircraft considered are:

- Strike (F-16, F-117, JSF, UCAVs, Hypersonic Vehicles, Airborne Aircraft/Missile Carriers, Micro Fighters, Micro UCAVs);
- Air Superiority (F-15, F-22, Tactical Missiles, Airborne Lasers, Laser/DEW Fighter);
- Air Mobility (C-130, C-141, C-5, C-17, Precision Airdrop, Next Generation Tanker, Long Range Transport);
- Long Range Bombing (FB-111, B-52, B-1, B-2, Global Bomber);
- Recce/Intel (RF-4, U-2, RS-71, AWACS, UAVs, Long Range/Endurance Aircraft Global Reconnaissance Aircraft);
- Special Operations (C-130, Autonomous Tactical Assault Transports);
- Access to Space/Support of Space Operations (Reusable Launchers, Manoeuvrable Re-entry Vehicles).

Note again that, like "New World Vistas", we have not treated trainers of their connection with the general aviation industry.

3.2 Design and Integration Issues

In addition to defining classes of missions and aircraft, there is another set of considerations that may determine the relevance, timeliness and the success or failure of a technology program. Some of those factors are:

- Changing missions, operations, external environments and loads;
- Changing emphasis on performance vs cost;
- Vulnerability, countermeasures, stealth and survivability;
- Inhabited vs uninhabited operations;
- Modular vs integrated design;
- Mode of takeoff and landing (CTOL, STOL, STOVL...);
- Propulsion - air breathing vs rocket;
- Interactions among aerodynamics, controls, propulsion and structures;
- Interactions among controls, avionics and structures;
- Changing roles among design, analysis, simulation, manufacturing and testing.

4. Required Airframe Structures and Materials Technologies

The following is a compendium of the needs for future R&D, as derived and interpreted from the above references. The arrangement follows the general Group arrangement of the AGARD/SMP.

4.1 Aeroelasticity, Loads, Dynamics, Active Controls

Basic research still is required in system identification, reduced order modelling, subscale (physical) modelling methods for structural dynamics non-linear instability states, impact, penetration and "reduced" scale modelling for aero-thermo-elastic designs.

On a more engineering level, there continues to be an unfilled need for affordable, robust transonic unsteady aerodynamic methods for the prediction of flutter and other aeroelastic responses. This needs to include methods to predict stability of non-linear systems at early stages of time-accurate computations of coupled CFD and structural interactions as well as affordable, rapid prediction and clearance to flutter case for multiple external stores. Robust, affordable methods are needed to predict unsteady separated flows for buffet problems as well as the large amplitude acoustic fluctuations in open weapon bays. Where it is necessary to include viscous effects, it may be necessary to completely rethink the mode of computations to obtain affordable (yet sufficiently accurate) computations.

Active controls will be needed for vibration suppression for optical benches in laser and directed energy weapons, active flutter suppression, active control of buffeting, the control of high amplitude acoustic fluctuations in weapon bays and active control of thermal input/response in high temperature applications.

In both civil and military applications, there is a need for efficient procedures for identifying critical loads cases (from among thousands of cases that might need to be analysed). Buffet remains very difficult to predict for highly manoeuvrable fighters, at least early enough in the design cycle. There also have been cases where "surprises" have occurred from non-linear flight loads in manoeuvres (longitudinal, literal-directional and combined) and at transonic speeds - even after considerable and analyses and flight testing. Digital controls and thrust vectoring will require updated manoeuvre loads criteria to reflect current and future pilot techniques. These can come (in part) from piloted simulations as well as flight tests and operations.

Where applicable, affordable and robust, steady and unsteady panelling methods still are necessary for prediction of flight loads for full three dimensional configurations. And, where necessary, affordable and robust steady and unsteady CFD codes are needed for full configurations with attached and separated flows.

Other requirements have been expressed for the design of active load alleviation with non-linear aerodynamics; the inclusion of dynamic aeroelastic effects on loads in discrete gust encounters; internationally unified gust criteria for non-linear systems; concurrent design of structural sizing and active controls and methods to determine coupled aero-thermo-elastic loads.

Continued development is necessary for structural test facilities that can simulate buffet by applying static loads in combination with high frequency random of sinusoidal dynamic loads.

4.2 Structural Design, Analysis, Optimisation; Smart Structures; Virtual Manufacturing

Continued progress will be necessary and is expected for FEM structural modelling methods for composite, sandwich and "smart" structures as well as the prediction of strength, stiffness and life of bonded repairs. More difficult, and just as necessary, is the development of affordable methods to integrate CFD with CSM - including the ability to predict stability or instability of the coupled system at early stages of a time-accurate calculation.

New thinking will be necessary to extend structural optimisation methods to apply to:

- Systems of modular aircraft, structures and subsystems;
- Design for low cost manufacturing, operations, maintenance.

Design for inspection by visual, audible and One hope for the future is that balanced, multidisciplinary, concurrent design, simulation and prototyping with:

- Virtual reality;
- Solid modelling;
- Feature-based design;
- Shared digital data bases.

will allow the formulation, placement and sizing of multi-functional structural members in highly efficient relationships that now may appear to be counter-intuitive. The result could be improved assessments of structural functionality, weight and cost. It may also be possible to achieve marked improvements in training and in day-to-day operations of fabrication, assembly, inspection, maintenance and repair.

One example of the need for new and expanded optimisation methods is that numerical optimisation of high speed transport configurations and structures will be mandatory. It may be impossible to reach optimum arrangements by traditional human engineering methods. In addition, when a modular aircraft is composed of (for example) different wings for different missions it is not yet clear how to pose the design of the wings, fuselage and their interfaces as a problem in optimisation.

One example of smart structures, active/adaptive aeroelastic surfaces, could enhance aerodynamic performance and manoeuvrability, while controlling loads, acoustics, buffet and vibrations. They also could improve weight, compensate for damage and incorporate some avionics/ECM functions.

Among other applications envisioned are active/adaptive aeroelastic surfaces for UCAVs; low observable, conformal load-bearing antennas and onboard health monitoring, including measurement of crack growth, delimitation and separation. These applications will require continued research on piezoelectric materials and the development of sensors, data bases, algorithms, processors with "memories", survivable networks and embedded, anisotropy actuators.

Even with the apparent promise of smart structures, there still have been repeated calls for statements of missions that justify their need and demonstrations of affordability, availability, durability and reliability.

4.3 Damage Tolerance, Durability, Fatigue; Fracture; Repair

There have been the customary calls for improved prediction of crack initiation and growth, leading to the computation of structural life in arbitrary stress fields. Ageing aircraft demand methods to predict service life and risk of failure, accounting for multiple site damage and corrosion fatigue. There is a critical need for detection of crack initiation and growth, exfoliation, corrosion, stress corrosion, corrosion fatigue and the prediction and/or measurement of remaining structural life.

Rapid improvements are expected and necessary in NDI, corrosion sensors and advanced diagnostics for health monitoring (architectures, sensors, networks and processors). This could include automated depot and field inspection methods without removing coatings as well as remote inspection methods using active optics, laser-generated sound, flexible fiber-optics and MEMS.

As engineered materials come into use, there will need to be understanding of their failure modes, just as in the case of three dimensional composite structures.

While continued progress is likely in high temperature acoustic and strain instrumentation, piloted hypersonic systems will require very expensive, national, full-scale test facilities that can combine high temperature with static and dynamic loads. As NDI capabilities develop for corrosion, corrosion fatigue and smart structures, increasingly sophisticated, large scale NDI facilities may be necessary.

Requirements for improved repair methods include FAA certified bolted repairs, depot and field repairs and (in the future) direct fabrication of finished components.

4.4 Materials, Structural Concepts, Processes, Manufacturing; Corrosion

In all materials studies there are the expected calls for high strength, light weight, durable, high temperature, high heat load, affordable, supportable, repairable materials. In particular improvements in all of these properties are needed for:

- Higher temperature aluminium alloys;
- Metal matrix composites;
- Materials for hypersonic vehicles and propulsion applications:
  - advanced titanium alloys;
  - superalloys;
  - intermetallics;
  - cryogenic materials;
  - titanium matrix composites;
  - ceramic matrix composites;

- Engineered materials - combining materials for best properties and minimum limitations;
- Multifunctional structural/electromagnetic materials;
- Non-silicon optical and electronic materials;
- Coatings, lubricants;
- Environmentally sensitive materials.

When materials move toward structural concepts, the studies issue the expected calls or affordable, low observable (radar, infra red, acoustic), inspectable, survivable and repairable concepts.

Some studies anticipate improved weight through radical structural arrangements, including graded structures to reduce joints and fittings. Hybrid structures of glass and graphite, in combination with textile pre-forms, could improve the durability and damage tolerance of fuselage members.

Unitised composite structures are expected to yield substantial cost savings. Other stated requirements for composite structures are composite fittings and low heat transfer, structurally reliable joining methods, including low cost bonding. As light weight, long life primary sandwich structures become feasible, demands will grow for their applications.

For high temperature applications, ceramic matrix composite reinforcements and primary aft fuselage structures will be required. There also is a demand for affordable, radar-absorbing, long life, structurally integrated (reduced number of parts) nozzles and aft-deck control surfaces in severe acoustic and thermal environments. There also are expressed needs for durable, long-life infra red heat shield; long life, durable copper, superalloy and carbon heat exchangers and carbon-carbon multifunctional structures (thermoradiators). Active and passive cooling and/or thermal protection may be necessary for high temperature as well as cryogenic structures.

For manufacturing there are the expected calls for improved, efficient "lean" materials processing and manufacturing (fabrication, joining, finishing). There is an emphatic need for improved scientific understanding, computational modelling and active control of all steps in processing metallic, composite and hybrid structures.

For metallic structures, requirements are expressed for improvements in manufacturing processes for a wider range of process temperatures for aluminium alloys, defect-free castings for primary structures. Rapid Solidification Technology (RST), welded aluminium-lithium, low cost induction-welding, superplastic forming, lower process temperature for concurrent superplastic forming-diffusion bonding and diffusion bonded titanium sandwich structures.

Requirements for improved manufacturing methods for composite include; three dimensional composites; resin film infusion (RFI) and resin transfer moulding (RTM) for fuselage frames and reinforcements; textile processes (weaving, knitting, braiding) for sandwich structures and for fuselage bulkhead, frames and bulkheads; low energy curing of composites and automated lay-up.

5. Conclusions and Recommendations

As stated earlier in this paper, the number of real and potential missions, aircraft and requirements for R&D are overwhelming to the technical leader who must allocate research personnel, funding and facilities. The formal processes to develop "requirements" have been ponderous, have emphasised the near term and have produced little usable guidance.

Scientists and engineers need long-term guidance to develop their capabilities and facilities. Yet they still want to be a part of a team that has definite directions - they don't want to be accused of "sandboxing".

In the United States, one promising improvement is the DOD method of "Integration" programs which is producing (among others) the Fixed Wing Vehicle (FWV) Technology Development Approach (TDA). Closely related is the development by some airframe companies (in co-operation with the government) of designs for "notional/baseline/referee" aircraft. Those design, coupled with experienced engineering assessments and mathematical optimisation techniques, have the potential to assist the authorities in government and industry to measure the cost/benefit relationships of candidate technologies. Of course we always must be aware of "breakthroughs" in technology or new missions, so the process needs to remain flexible to incorporate those considerations.

The continual erosion of resources is compelling the military services and NASA to greater co-operation in the planning and execution of their R&D programs. The FWV/TDA program, in co-operation with an evolving program of "notional" aircraft designs, will assist that co-operation for fixed wing vehicles. There are some indications that industry is examining its internal R&D programs, with an eye to separating their "competitive edge" programs from those which might be termed "pre-competitive". The idea is that the several aircraft companies (each in its own self interest) might be open to collaboration in some of their basic research, "pre-competitive" R&D and facilities. Then the industry could direct a greater proportion of its resources to where they perceive a "competitive edge", while replying on collaboration, DOD, NASA and academia to continue the technology base.

Certainly the AGARD/SMP has been a leader in such collaboration. The self-interests of all the member nations, their industries and their R&D institutions might be served by even greater co-operation within NATO.

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Seamless Transition from Product Concept to Production and Deployment

John Coyle

Rapidly changing computing capabilities and simulation software have created the potential for an affordable product and process development protocol for new products. The concept of an Integrated Collocated product design team has already given way to an electronically collocated design team that functions in a synthetic environment without regard to company structure or national boundaries. The simulation and modelling toolset and supporting computational capabilities are exiting the twentieth century at a breath taking pace. The war fighting simulation models and distributed simulation tools have created the capability to experience near real engagements for tanks, ships and aircraft in a synthetic environment. Physics based simulation or products and processes are continuing to improve the modelling capability for synthetic test.

The architecture shown below demonstrates the integration of many databases into a seamless toolset that uses and reuses the same data sources from the earliest design concepts through the manufacturing and deployment phases of the program.

At the conceptual design stage the design team is able to evaluate the performance characteristics of a variety of configurations and trade off performance versus cost at the earliest stages of development. Virtual Operational Evaluation is a capability to "fly before buy" the product based on the users requirements including performance and physical characteristics. The distributed simulation capability will enable the integration of war fighting scenario with product performance simulations and discrete event representations of the product in its operating environment.

Virtual Manufacturing and a Virtual Prototype are capabilities to validate the product design and production processes in a synthetic environment which will result in an initial production unit fulfilling the performance requirements with no rework at the lowest possible total cost. Virtual Manufacturing and Virtual Prototypes are developed from the CAD solid model representations of the product design and initial tool concepts enabling manufacturing involvement from the concept phase through the Build To phase. The combination of the Integrated Design and Analysis Tools and Virtual Manufacturing being developed and integrated among the Aerospace companies have demonstrated the potential to reduce the design to first unit build cycle time by 33% with 25% less people than were used for equivalent efforts.

The Virtual Manufacturing and Virtual Prototype tool set includes new tools for Assembly Simulation, Process Flow simulation and NC Machine Tool Simulation which are integrated with the CAD system, MRP, Scheduling tools, time standards, work instructions and planning. The Virtual Prototype is a design related activity that integrates the design concept and the manufacturing concepts for producibility and affordability. The Virtual Manufacturing activity starts with the Virtual Prototype and continues through the design and first unit planning phases to create a manufacturing plan. This tool integration is planned to occur within a Product Data Manager environment.

Virtual Manufacturing objectives are:

- Reduce the risk of transition into production;
- Mature the product and process design in a synthetic environment;
- Eliminate need for LRIP phase;
- Reduce unit cost through avoidance of rework;
- Optimise production plan in a synthetic environment.

Virtual Manufacturing benefits are:

- Lower T1 labour cost (33% labour decrease);
- Reduce rework (Boeing advertises 90% reduction);
- Reduce sustaining engineering effort (50% target);
- Reduce production cycle time;
- Simulations reusable for operator work instructions;
- Simulations reusable for maintenance tasks;
- Reduced planning costs (NR).

Virtual Manufacturing (VM) is an integrated, synthetic manufacturing environment that can be exercised to evaluate impacts to the manufacturing process to evaluate the producibility and affordability of new or existing products. VM enables the preparation and validation of high quality manufacturing plans in the synthetic environment before the product and process designs are released.

Assembly Simulation is the visualisation of the assembly process in a 3D environment including the product, tools, machines and processes as well as the human interface in a realistic synthetic environment. The visualisation and analysis of the part motion recognises collisions and "near misses" to evaluate "part to part" and "part to tool" fit. The cycle times are representative of the factory processes which will be ultimately implemented. The human models introduced in this environment include the human factors analysis of Niosh reach and lift limits as well as energy expended and industrial engineering time standards. The vision is that the 3D models are derived from the solid models in the CAD database and are capable of seamless transition into the process flow simulations described below.

Process Flow Simulation is the mathematical modelling of fabrication or assembly operations in a discrete event, multiple resource, simulation. The analysis of these simulations allows the evaluation of alternative processes, rates, worker skills, resources and inventories. The simulation outputs for a given scenario include the number of people required, skill mix, number of work stations, impact of multiple shifts, cycle time, queuing problems, inventory levels and total cost. Simulation tools use either 2D or 3D visualisation packages to display the process for ready understanding. The vision is that the precedence of assembly required for these models and the process visualisation be derived from the Assembly Simulation process described above reducing the time to prepare the process flow simulation and enhancing its usability through the 3D visualisation. The integration of assembly simulation and Process Flow simulation is the basis for a product cost estimate which incorporates material costs and labour costs from the synthetic product planning.

Machine Tool Simulation is the use of 3D graphical software tools to verify machine tool and robot motions prior to release of numerical control (NC) programs to actual production. The ability to visualise machine motions, detect collisions with the machine and tools, and mimic the controller post processing of the programmed motions validates the program eliminating the need for first piece program verification parts and related rework costs. The ability to derive the 3D graphical images directly from CAD and the capability to return the "as made" part model to CAD in a parasolid kernel is consistent with the vision of seamless transfer between the engineering CAD environment and the synthetic environment.

Virtual Prototype is the assembly of the product in full detail into the finished product through a series of move sequences of 3D models in a synthetic environment to demonstrate access of parts as well as fit prior to completion of the design. This is often described as a "fly through" design review and/or a virtual collaborative prototype with multiple participants who are not collocated. Virtual Prototypes generally are 3D solid models derived from the CAD design environment and viewed in an immersive or virtual reality environment. Key characteristics for a virtual prototype include the capability for multi location simultaneous viewing and a capability to detect fit problems (near miss and collision) and "mark" these areas with a capability to return to the CAD environment through a parasolid kernel. A virtual prototype and design review process are essential to achieving the reduce cost and cycle times projected.

Virtual Reality (VR) is a tool which may be used for Virtual Manufacturing, Virtual Prototypes, Operating Training and Maintainability training. The VR tool requires a seamless translation from the CAD environment to the VR environment with a mathematically correct visualisation of the product and tools. VR enables the interaction of the individual with the tooling and parts in the virtual environment.

Immersive capabilities should support multi person viewing through glasses, projection as well as individual immersion. The vision recognises VR as a viable tool for design review, operating training and maintainability training. A seamless, user friendly, interface to the CAD tools is essential.

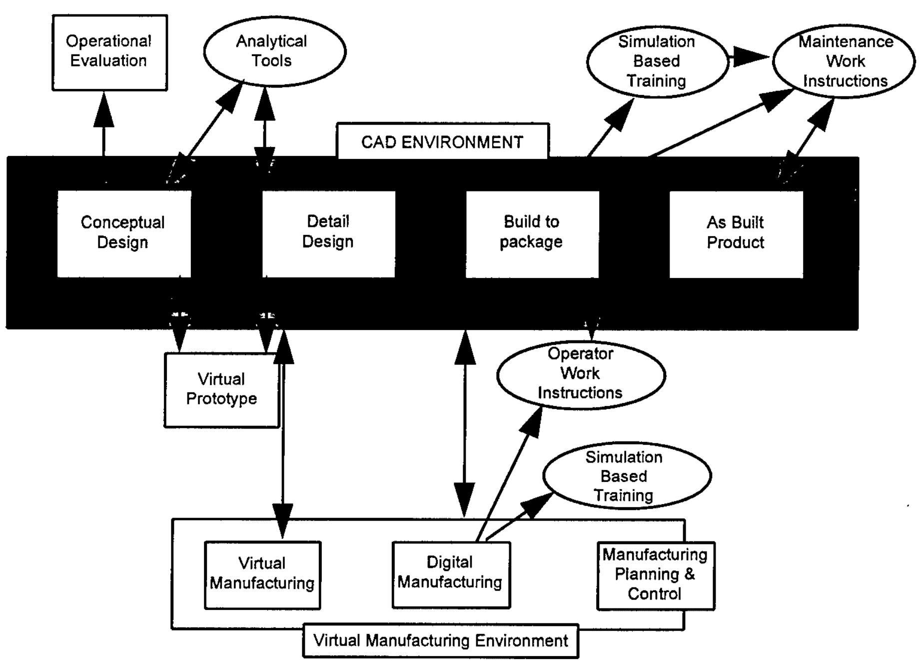
Operator Work Instruction with utilise browser technology and visualisation to present effective instructions which reduce learning and increase the quality of work performed. The VM tools selected should provide for the reuse of the CAD 3D images and assembly simulations to optimise the operator learning. Delivery of work instructions using multimedia presentation including visual, sound and printed instruction in an intranet browser offers the most effective process. Early demonstrations show the benefits of assembly visualisation and VR in improved operator performance. Additional studies will be required to delineate the best practices for each type of work. The reuse of solid models and simulations as part of work instructions is consistent with the vision. Further work is required to integrate shop floor data collection in the same process.

Architecture for the toolset and its integration with the manufacturing operating systems will occur through a CORBA based data management system which accesses the Time Standards, MRP II, Planning and Scheduling systems and financial systems. Emerging software tools are expected to facilitate access to legacy systems which will mitigate some of the cost of implementing the virtual manufacturing technology.

The key factors learned through experience includes an emphasis on program to program compatibility.

CAD translators have been and to some extent remain a weak link. Software that utilises 3D images must be CAD compatible. The capability for two way linkage between simulation software and CAD has always been a goal and generally not practical. The over arching vision is a seamless transition from a common solid geometry model to the analytical tools combined with a seamless integration of the VM tools to assure a single, high quality design which is the basis for all activity.

Affordability is achieved through reduced engineering changes in the product design, tool design and process implementation. The average unit cost of the first ten units should reflect the benefit of learning in the synthetic environment. The reuse of the CAD solid models for visualisation of part to part fit and part to tool fit provides new tools for all members of the Integrated Product Team throughout the product life cycle from the conceptual design to the field maintenance Simulation Based training and work instructions and reduces non recurring costs. The application of virtual prototypes and virtual manufacturing does not increase development cost but changes the skill mix for the team.



Integrated Airframe Design Technology

Otto Sensburg

Integrated Airframe Design Technology is an important element of a number of activities required to improve the business performance of Aircraft companies worldwide.

The customers require more reliable products at an affordable price that perform to specification and are easy to support in service.

The time required to design and build an aircraft needs to be reduced also an environment created whereby all parties involved can work together to influence the development of the design at an early stage.

This approach coupled with enhanced visualisation and simulation of both the functional and physical elements of the product design will enable modifications to be implemented as part of the design process before the start of manufacturing/build. Thus the need for changes to be carried out during and after production build will be significantly reduced and will result in impressive savings in costs.

Integrated Airframe Design Technology provides the basis for this new environment to be developed.

The introduction of technological innovation into aircraft structure usually is not a continuous process, in most cases there are technology pushes, as there has been the change from wood to laminated wood, to metal, to composite, and maybe to smart materials and smart structures in the future. There are two main reasons for these technology jumps:

1. The lifetimes of aircraft usually are 25 to 40 years, and it is the exception to introduce new structural technologies into existing designs due to cost and airworthiness reasons;
2. The development of new materials and introduction into structures is itself a process which lasts 10-20 years.

Therefore, it is important to start the development of a new aircraft design and to have a fully matured structural technology available that can be introduced without risk into the design.

In the past, the major technological pushes in new materials and structures have been driven by the weight-saving potential due to higher specific strength of new materials. The introduction of new materials was promoted by material and structural design engineers and, as the weight saving potential has been so big, the question of manufacturing costs could be easily answered in favour of the new technologies, especially in military aircraft designs, where the increase in performance often rules out the cost aspects. But this has changed dramatically in recent years.

The ability to build lightweight structures will always be a dominant factor for flying articles, and therefore, all possibilities of finding optimum designs must be available such as:

1. Mathematical optimisation codes in preliminary design stages including tailoring for composite materials;
2. Load alleviation and active vibration control to reduce loads and reserve factors;
3. Efficient codes for analysing structures that are all interconnected.

Airlines and air forces have to consider life cycle costs of aircraft and therefore, the fly-away-price of the aircraft structure is only one factor within the life-cycle costs.

Consequently, the aspect of design-to-cost, to manufacture, to assembly, to reliability, and to supportability have become key issues already in the conceptual design phases of new aircraft.

The implications of these requirements for technological innovations in the field of aircraft structures are as follows:

1. Manufacturing and assembly technology should be fully developed at the start of the design phase. This includes the aspects of reproducibility, quality assurance, health hazards, and the question of advanced production techniques. But most important will be, whether the design-to-cost data have been developed and justified well enough to allow the introduction of new technologies at a reasonable risk.
2. The aspects of reliability and supportability have to be covered from the very beginning. The problem is to make qualified forecasts for all lifetime of 25-40 years on the acceptability of materials to environmental degradation, because "real life" tests are not possible due to time constraints.
3. Also, the issues of material qualification, development of design allowables, and design methods have to be addressed before the start of the design phase. This requirement is no longer as dominant as it was in the past.

The management of technological innovation has to take into account concurrent engineering aspects as never before. The challenges, which have to be addressed, are to foresee the most promising features in the development of new materials with respect top advanced aircraft concepts, and to start a well-timed concurrent engineering action promoting the most critical research issues for the implementation of advanced technologies into new aircraft designs.

The time span between new aircraft projects is becoming larger and larger, and flying demonstrators will be of increasing importance in the future. This approach to assure the airworthiness of new technologies and to develop at least a limited amount of in-service experience for new concepts will promote the introduction of technological innovations into the design of new aircraft.

The full potential of integrated design methods should reduce the necessary design effort to 50% of the conventional effort.

In recent years, composite materials have gained an important role in airplane construction. Due to their superior lightweight structural characteristics, especially carbon fiber reinforced plastic materials (CFRP) can save more than 40% of weight in a modern fighter aircraft design. On the other hand, using these new materials can result in a considerable reduction of parts compared to traditional metallic designs.

Integrated Product Development/Concurrent Engineering

Integrated product development (IPD) or concurrent engineering is a systematic approach to the integrated design of products and of their related processes, including manufacturing and support functions. The design process needs to be carried out through integrated work teams with the participation of all the involved functions. This means having everyone involved in the early design when the cost of a design change is small so that the design changes during EMD (engineering and manufacturing development) and production are few (when the cost of design change is large). This IPD approach is shown below and compared with the serial or traditional approach.

Low Cost Manufacturing

Verner J Johnson and Richard C Holzwarth

Current design studies and ongoing structural demonstration activities predict that in order to simultaneously achieve the weight and cost goals for future aircraft structure, there will be a strong reliance on the concept of increased structural unitization. Structural unitization refers to design concepts that minimise the total number of fabricated parts joined in a structural assembly. Contemporary aircraft structure is manufactured through the mechanical assembly of numerous small parts. Although often simple to fabricate individually, the assembly process requires high expenditure of labour, many assembly tools, and thousands of fasteners. Use of many detail parts lead to structural discontinuities, reduced efficiency and increased weight, and the fastened assemblies are prone to corrosion and induced fatigue. Structural unitization will eliminate these numerous, and often redundant small parts, and significantly reduce the weight of air vehicle structure as compared to current design approaches. Structural unitization also has significant potential to reduce the life cycle cost of airframes by reducing fabrication and assembly cost during manufacture, and reducing maintenance cost during service. These cost reductions have been predicted in several design studies based on existing and future aircraft, and achieved, in a limited manner, in some actual demonstration activities. Whilst current technology development programs are identifying potential approaches to more integrated structures, in order to fully achieve unitised structure, several existing barriers, both technical and philosophical, must be overcome. In order to eliminate the numerous small structural components, especially in the area of joints, the structural design concept must emphasise smooth, continuous, distributed loads. This is very difficult, particularly in fighter fuselage structure, due to the large number of concentrated loads introduced by landing gear, weapons attachments, and engine and subsystems installation requirements. Therefore, provision for the smooth transition from concentrated loads to distributed loads, within a highly constrained volume, must be made during conceptual design. The manufacturing processes to achieve effective integrated structure must also be considered. The individual parts may be more complex to fabricate. Although the number of assembly steps will be driven down, great care must be taken in order to design a structure that can be integrated with increasingly complex vehicle subsystems. One potential solution to this problem may be to use the structure itself as part of the subsystems. The structure may function as an antenna, and have provision for electrical, optical, or fluid transport included in the actual airframe by having the various "busses" fabricated into the structure and "integrated/installed" in the airframe as part of the structural assembly. Current aircraft usage trends indicate that future weapons systems will be designed for increasingly longer lives. More integrated structure will obviously be more complicated to repair through common remove/replace philosophies. Therefore, more integrated structure must be more robust in order to avoid complicated and costly repair. This robustness must also extend to the manufacturing process, as very large parts representing major airframe components must be manufactured correctly each time. One characteristic of unitised structure may be a significant decrease in the number of redundant subcomponents, such as the number of spars in a wing. This could have a major impact on both damage tolerance and survivability, and design approaches that allow low cost unitised structure and meet the more difficult survivability challenges of future threats must be developed and implements. Developing the technology to implement more unitised structure will seriously challenge the aerospace structures design and manufacturing community, however, no other approach has been identified that can enable the cost and weight reduction goals identified.

Many conventional methods of designing and manufacturing structure will have to be significantly revised in order to achieve the cost and weight reductions postulated. One area of emphasis that has significant payoff is the combination of real time statistical process control to maintain particular levels of quality in manufacture coupled to probabilistic design methods to reduce current design conservation. Statistical process control can be used during the manufacture of the structure to assure that the properties, parameters, and even geometry's, assumed in the design of a structure are those maintained during the manufacture. The implementation of such a concept goes far beyond the factory floor - the understanding of the effect of variations in materials processing, environment, and structural history on the residual strength of the structure will have to be understood and predictable. There is some synergy available from several emerging technologies, particularly structural health monitoring. The effects of variation in the material or manufacturing environment, and use environment can be quantified. The structure is then designed for a specified level of reliability. It may be possible, particularly in composites, to use a single integrated sensor suite to monitor the environment that the structure experiences during manufacture and use the information to control the manufacturing process

such that the initial quality is assured to be satisfactory to the design requirements. It may be possible that these same sensors can be used during the life of the aircraft to determine the actual health of the vehicle - to be certain that the actual environment is within the limits of the design environment. Such an approach, when implemented, will reduce or eliminate many of the costs of inspection, either as quality assurance during manufacture or as safety assurance during usage. Due to uncertainties in material properties and load conditions, coupled with concerns for durability and damage tolerance there is a substantial amount of redundant structure in the airframe. This redundancy has several forms, including structure that is oversize, or overly complex to effectively perform its required function. This structure has considerable cost beyond that of its manufacture. The additional weight of this (inefficient) structure imposes growth and therefore cost on the rest of the airframe and other systems. Elimination of the conservatism inherent in current design practice by demonstrated control of the source of variation will eliminate the need for such conservatism.

There are, at the highest level, two specific approaches to achieving more unitised structure. The first is to employ methods of fabrication that eliminate the need to build up structure from smaller constitutive parts. Several of these processes showing promise to reduce the manufactured cost of aircraft structure will be discussed later in this paper. The second method is to employ more effective methods of joining the separately fabricated parts into assemblies. Mechanical fasteners, bolts and rivets, will still be used based on load requirements or the need to disassemble the structure. However, it is clear from ongoing technology development efforts that welding and adhesive bonding of structure will become more common. Adhesive bonding, which can provide a layer of more compliant structure between the two adherents, show significant promise to overcome some of the shortcomings occurring today in the joining of dissimilar materials, especially in areas where there is a thermal expansion or stiffness mismatch. Adhesive bonding shows the potential to reduce assembly cost through the elimination of numerous fasteners, and the associated nut plates, splice plates, clips and other miscellaneous parts. Additionally, adhesive bonding itself is relatively robust with respect to location and, when well designed and executed, is self shimming. Adhesive bonding also allows a more distributed and lower intensity load within the joint, reducing the need for pad-ups, thickening strips, changed lamination schemes and other manufacturing complexities that increase cost. Inspection is problematic with both adhesive bonding and welding, however, the probabilistic design and statistical process control approach have particular merit here. There are also concerns for ballistic survivability, but recent research program results indicate that a well designed adhesive joint has actual survivability benefits. Adhesive bonding can also be combined with other joining approaches. It may be desirable to join highly loaded structure as typically joined by bolts and/or lugs, by using tongue and groove type joints where the tongue and groove are adhesively bonded. Such a joint will simplify the load path and reduce the load intensity, eliminate the requirement for two sided access, reduce the need to inspect the joint for corrosion and fatigue, and may increase the tolerable manufacturing variation and reduce tooling expense.

It is unlikely that future airframes will be composed of a single component manufactured from a single material system. Therefore, improvements in joining technology will be a major influence on both the design concept and manufacturing process for future aircraft structure. Joining structures made from dissimilar materials is a fruitful area for both cost and weight reductions. A manufacturing procedure currently under limited investigation for joining dissimilar metallic alloys is explosive joining. Explosive joining is used in manufacturing some US coins and is a mechanical joint formed by the explosively forcing two sheets together. One of the current investigations looks at explosively joining aluminium upper and titanium lower sections of a fighter bulkhead. A second investigation concerns the range of possible applications for explosive joining and will include innovative approaches for polymer composite to metallic structural joints as well as metal to metal joints.

An obvious approach to joining advanced composite structural "subcomponents" into "components" (to use current terminology) is increased use of cocuring in the manufacturing process. Cocure of composites is the process through which small parts laid up or fabricated separately are placed in contact with each other in a mould and cured into a single piece. When a layer of adhesive is added between the parts the process is referred to as cobonded. The cocuring/cobonding process is in use today, and is producing ever more complex structure, but is still limited in application due to several shortcomings. The first, and perhaps most significant, are shortcomings in the composite material systems themselves. Most cocured composites are fabricated using pre-impregnated tow, tape or broadgoods. These structures still demonstrate a major weakness with composite materials, insufficient material strength through the thickness of the material, and require mechanical fastening and additional (often metal) substructure to react the combined load. Developments in through thickness reinforcement, stitching, z-pinning, braiding/knitting, will overcome this shortcoming. The other major problem is the complexity of the cocure itself. The fabricated part and tool must be designed in such a manner as to

allow all of the material to be placed accurately in the tool. This often comprises load path management, structural concept, geometry, fiber alignment, and material form. The e tool is complex to manufacture and therefore expensive. Recent improvements in the use of electron beam (e-beams) to cure composite structures indicate that these shortcomings may be overcome for future aircraft.

The electron beam curing process takes advantage of the fact that some resin systems can be formulated to initiate the curing process after being subjected to an electron beam of approximately 10Megarad. This process has the potential to reduce the complexity and cost of conventional tooling, as typified by autoclave type processes. Most work with e-beam cure composites assumes dry prepreg material and some form of automated lay-down such as automated tape lay-up or tow placement. There is no reason, in principle, why it could not be used with wet lay-up methods such as filament winding, or even conventional wet lay-up of cloth. Unlike oven or autoclave cured processes, e-beam sensitive composites may be cured in stages, allowing more flexibility in the fibre architecture, and enabling use of various through thickness reinforcement schemes that can react higher combined loads than conventional composites. Another use of the e-beam process could be to cure adhesives in a bonded structure, providing more consistent bond quality.

Resin Transfer Moulding and Resin Film Infusion are two fabrication concepts that support the philosophy of unitised structure. In these processes, dry fibrous preform material is placed into a closed mould. Liquid resin is then introduced into the mould through forced injection or vacuum infusion. RTM/RFI has already demonstrated the capability to manufacture complex shape parts capable of reacting high loads, at least in primary directions. One major advantage of the RTM/RFI approach is that the parts emerge near net shape, requiring little finishing activity other than some trimming or drilling for fasteners. Another major advantage of RTM/RFI is that it is very compatible with preform fabrication techniques that allow for non-laminated composite structure. RTM/RFI approaches today are constrained by tooling costs. The more complex the part, the more expensive the tool and the more difficult it is to get satisfactory resin penetration. Efforts underway to generally reduce the cost of tooling for advanced composites could have significant payoff here. Currently, RTM/RFI approaches require high production numbers to have cost benefits, over more common fabrication approaches, reductions in tooling cost will allow wider use of this approach. Another potential use of RTM will be to produce "b-staged" or partially cured near net shape complex composite structures that could then be cocured or cobonded (perhaps through e-beam) to less complex structure fabricated using another process. An example of this approach would be to fabricate a highly loaded complex structure, such as a wing weapons pylon mount using a combination of braiding and z-fibre insertion in order to achieve the required strength in three directions locally and knitting alone in the area where the pylon distributes the load into the spars and skins. This fibre preform can be "b-staged" with an e-beam sensitive resin system and joined to a more conventionally laid-up wing skin (tape laid?) and spars (braided?) through e-beam initiated cocure.

One promising new development in material technologies that shows great potential for increased structural unitization is the pultruded composite rod. Commonly produced using Fiberglas for the communications industry (they provide support for fibre optics), graphite reinforced rod material can also be manufactured in varying widths. Provided by the manufacturer on a creel, the rods can be placed in a process similar to tow/tape placement. A significant advantage of these rods is the ability to precisely control fibre location and alignment, providing significant increases in tension and compression strength. The rods can also provide a framework around which more conventional fibre, cloth, tow or tape may be formed. The rods reduce manufacturing cost be controlling more precisely where the fibre is in the structure, and reducing the complexity of the manufacturing problem. A relatively small number of rods can replace several layers of tape or tow, reducing manufacturing flow time. The lower scatter in property values observed in rod performance, and the generally higher property values indicate significant opportunity to reduce design conservation and increase tolerance for manufacturing variation.

Superplastic forming (SPF) and superplastic forming in conjunction with diffusion bonding (SPF/DB), especially for aluminium and titanium respectively are respected processes for complex, thin sheet structural parts and have been used for thousands of small complex parts to generate cost and weight savings on the current generation of USAF aircraft. Relative to baseline designs, weight and cost savings vary from 0-60% depending upon the application and the baseline. Only for the F-15E aft fuselage structure and the B-2 aft deck have sizeable structural parts been made. Various US companies and government agencies have efforts under way to expand use of the manufacturing process to large sections. Many barriers to further benefits are opportunities for evolutionary development, but major barriers being addressed that may expand future applications to large structural sections are tooling cost, sufficiency of data, inspectability, design technique, and design allowables.

Castings are regarded as a relatively inexpensive manufacturing process for unitised, non-critical

aircraft structure. The major benefit of castings is that complex structural components can be fabricated in a single piece, replacing many simply shaped machined or formed subcomponents that are riveted or mechanically fastened together. The result is reduced part count, fewer manufacturing processes, and lower cost. Aluminium castings are used in a number of major but non-primary aircraft structural components such as pylons, canopy frames, and inlet duct structure, usually with casting factors which cause additional weight and cost for the component. An advanced development cast aluminium transport landing gear and nose pressure bulkhead developed and manufactured without casting factors saved 35% in cost relative to a built up design. Uniform thickness titanium castings subject to predictable loads are used extensively in turbine engine components without casting factors. Recent work with control of constituents and casting quality have shown titanium castings useable for primary structure, also without casting factors. An advanced development fuselage bulkhead showed a 40% acquisition cost savings relative to a forged baseline bulkhead design; additional savings will accrue from reduced supportability of operating aircraft. One production primary titanium structural casting new exists. renewed industry and government interests in castings for unitised primary structure will make large cost savings real in the next generation of aircraft. With this interest will come the design allowable that have in the past restricted use of castings for primary structure.

Spray forming as originally developed by Osprey Metals Ltd, has been exploited by producers, universities, and government agencies for manufacturing otherwise unproducible alloys, metal matrix composites, and small structural elements in a research environment. Spray forming of metals can be used to economically form both sheet and structural shapes of graded and nonuniform thickness sheet, plate, and complex structural elements. Visionary applications to manufacturing and repair of aircraft structures include manufacturing large integrally stiffened panels where both the skin and the stiffeners have variable depth and thickness. Spray formed panels may possibly be created with sensors and piezoelectric elements integrated into the panels for use as smart structures or channels may be built in or sprayed in for cooling purposes as the panels are being manufactured. Potentially, structure from operating aircraft could be spray formed to repair or renew damaged or corroded components. There are numerous challenges to be faced in the visionary applications of this manufacturing technology. Flat plates and tubing may be thermomechanically treatable, but treatment of complex structure is another matter. Repair of damaged structure may require removal from the aircraft unless innovative cooling procedures are also developed for use on the effected aircraft. Spray nozzles of various size and shape, tooling and techniques need development before far reaching applications are possible.

Several welding techniques are under development in the US. They include laser and friction stir welding which result in joints with minimal distortion and detrimental metallurgical effects. Both approaches can be used to manufacture structures composed of planar and non-planar joints to produce integral metallic components that make up a complex aircraft structure. Use of welding allows replacement of mechanical fasteners as an assembly means and consequently provides more economical and lighter weight aircraft structure.

Successful implementation of more utilised structure will not occur unless the design and integration of the other systems within the air vehicle are substantially changed. Currently, various subsystems are installed within the structure as the structure is built up, indeed, the subsystems are often built up one component at a time themselves. This is due partially to the improved accessibility of the incomplete structure, and partially to the work flow requirements of the factory. It is clear that structural components that emerge from fabrication process as a nearly complete assembly will have less accessibility for the installation of subsystems. A probable solution to this sequencing problem will be adaption of more modular integration schemes for the required subsystems. In a sense, the subsystems will be more utilised also. The unitised subsystems will be installed in the air vehicle as nearly complete modules. This will be greatly aided by advanced subsystems concepts such as the all electric aircraft, in which hydraulic systems are completely eliminated. The electrical power network could be built into the surrounding structure, along with the (optical?) controls network by including them in the fabrication of the structure. provision for installation of the appropriate devices, such as control actuators, could also be designed into the structure itself, so that as the device is physically located on the structure, it is also installed and connected. Installation of electric control actuators, for instance, could become a "plug and play" type event, in which by mounting the actuator, the controller and power supply are also connected, leaving only the actual physical connection of the controlled. An even more sophisticated approach could utilise shape memory alloys as the control actuator, or even the controlled surface itself, so that merely plugging into the power/control circuitry installs the control.

A key factor enabling low cost manufacture through the effective integration of vehicle subsystems with unitised structure will be better, more effective design tools. These tools, which are emerging today, will couple solid modelling with engineering analysis capability at a high level of fidelity. More than a

virtual representation of the structure, the models will also have to account for all of the integration aspects of the other aircraft systems, interconnects, clearances, tolerances, interference's. Models developed at this level of fidelity will allow simulation of the function of the installed systems and their influence on the performance of the aircraft mission. Functions that once required flight test to evaluate could be "tested" in the virtual form. The long term payoffs of these tests is far greater than aircraft performance within the design envelope. The interaction of controlled surfaces and flight controls could be evaluated. The relationships between installed components and the base structure, or other components, subjected to flight loads can be examined. These interrelationship tests should include the ease of manufacture and assembly, manufacturing sequence development, future modifications, maintenance procedures. These models would be capable of analysis with respect to standard engineering parameters, such as stress/strain relationships, but would also be able to predict cost as a function of some standard parameter related to assembly functions, and not to overall volume or weight. Today, cost conscious designers try to predict and control the cost of the element of the aircraft they are working on. The aircraft final cost is the sum of the elements. Cost goals are set for the aircraft, and apportioned to each component. These virtual prototypes could be used to look at the influence of the integration of the elements on cost, and select the design concept and manufacturing processes that have the lowest overall cost for a specified level of performance - cost becomes an independent variable to be optimised instead of a pre-determined goal to be achieved.

More unitised structure should also reduce the need for sophisticated final assembly tooling. Again, this has benefits beyond the assembly of the structure itself. Structural modules, with the required subsystems pre-installed, can be brought together on the factory floor with a minimum of associated jigs and fixtures. Design concepts that utilise this approach are already in use, in a simplified form, in civilian sailplane and recreational aircraft. Major aircraft components, wings and fuselages, with all required subsystems installed, can be brought together and attached at a few specific hard points. These points can be designed to be largely self locating, and be designed so that physical contact also gives as many of the subsystem component interconnects as possible. Again, reliance on more electric subsystems greatly increases the potential for such a concept. During the installation of the subsystems, the structure itself could be used as the locating jig for the subsystems, with key reference points for installation fabricated into the structure. Future factories could be set up with various forms of flexible, robotic assembly equipment that could complete major assembly tasks for varying types of structure/vehicle components. The same "locator/assembler" machine could be used to complete tasks on different assemblies based on production schedule, relying on different programming instructions for the different assembles, or even "reading" the assembly instructions directly off of the components as they are provided.

Several specific technologies relating to design approaches, design concepts, and manufacturing processes are being developed now that will lead to more integrated structure for future airframe. Unitised aircraft structure will be combinations of advanced composite and metallic structures that allow for designs with reduced numbers of fabricated parts and assembly steps. Material selection will be made on the basis of load condition and intensity, temperature range, specific strength, specific cost, or critical factors based on structural application. Low cost manufacturing will be influenced primarily by design, with no single material system or manufacturing process being the preferred path. Design concepts that emphasise more unitised structure are synergistic with manufacturing processes that emphasise fabrication of articles that are virtually the finished product. Systems integration issues are major players to achieving low cost manufacturing, and new approaches to design and manufacturing of these subsystems are critical.

Maintenance-Free Aircraft

Steve Welburn

Introduction

Although the ultimate aim of a *maintenance-free aircraft* may never be achieved, the Aerospace 2020 report highlights the huge cost savings that would result from a substantial reduction in aircraft maintenance costs. The route to achieve these savings has to be via the correct specification of reliability targets for the next generation of aircraft procurement. In particular, reliability throughout the complete mission should be specified as a prime operational performance characteristic of new equipment as it is the ultimate verification of the effectiveness of any weapon system. However, as new equipment to meet new missions becomes increasingly complex, the specification of mission reliability, and the subsequent assurance that the required reliability has been delivered, becomes extremely difficult. Life Cycle Costs (LCC) need to be addressed from the earliest days of a project, in feasibility studies, and followed through into the design and acquisition stage since 90% of LCC may be determined by the decisions made before production of a new weapon systems begins. This paper highlights the emphasis now being placed on maintenance free operating periods for aircraft rather than the traditional approach of assessing mean time between failures for individual equipments.

Reliability, Maintainability and Testability

The classical approach to contracting for a reliable defence equipment was to put an optimistic figure for Mean Time Between Failure (MTBF) in the specification and trust that, through development and production reliability testing, in-service equipment would perform satisfactory. However, the cost of demanding increasing reliability maintainability and testability (RM&T) from every single item in a weapons system has to be borne in mind. Affordability in LCC terms is now becoming accepted on an equal basis with performance criteria, and underpinning affordability is the need to drive supportability cost down. Specifying reliability in terms of failure rate or MTBF is not in the best interests of customer or supplier. From the customer's point of view, it does not adequately describe what is really required which is equipment which does not fail in service. What the customer really requires is failure-free operation and, in aircraft structures with a safety implication, a failure rate is most definitely not required. MTBF does not lend itself to a straightforward contract for the supplier since, being of a probabilistic nature, demonstration of compliance is dependent on the confidence levels required and this may result in very long test period.

The time to Failure approach, often known as the Physics of Failure, demands:

- A thorough knowledge and understanding of the environment in which the equipment will operate.
- A good understanding of the material properties used in the design.
- Knowledge of the way things fail under the various degrading influences.
- Analysis of field failure data which supports the acquisition of knowledge of how the failure occurred rather than the mere summation of failures over time.
- Control of manufacture to reduce variability.
- An acceptance that condition-based maintenance *may* be needed.

This overall approach contains nothing new to the structural design engineer but what has been lacking, particularly for systems designers, is the sophisticated support modelling and analysis tools. Such tools are now becoming more widely available in industry to examine trade-offs for RM&T against availability. British Aerospace has a simple model which looks at linking LCC to value for money, weapon system acquisition and other parameters, with the concept of support as a main feature of the model.

Fault Free Operation Periods in Aircraft Design Philosophies

Setting a realistic and justified reliability requirement in terms of a Fault Free Operation period (FFOP) has much to recommend it. If the failure results in catastrophe, then the FFOP should be considerably larger than the actual period of use, whereas if failure can be tolerated operationally, the design assurance activities relating to the confidence required in the FFOP need not be so exhaustive. The UK's Safe Life design philosophy for aircraft structure sets out the necessary safety factors and procedures to ensure that the life demonstrated by the manufacturer is, for practical purposes the weakest example of a structural component that could enter service. This philosophy means that throughout the design life of the fleet there should be no fatigue-related structural inspections but, inevitably, there are occasions when

the aircraft loading is more severe than anticipated or there are shortfalls in design, which result in the introduction of inspections or airframe modifications. The Safe Life philosophy was deemed by many, particularly the USA, to be uneconomic because of the useful life which was being discarded in the majority of the fleet. This can be an important consideration for readily inspectable structures, such as those of large transport aircraft. Hence, the Damage Tolerance (DT) philosophy emerged which accepted that the structure must retain adequate strength and stiffness, despite the occurrence of cracking, until such time as the damage was found and repaired. In the future, the sophistication of structural modelling tools should permit the design to be optimised for FFOP, along the lines of Safe Life, whilst understanding the failure mechanisms that could require a limited reversion of an inspection-dependent regime.

Maintenance-Free Operating Periods

The FFOP approach is entirely consistent with the principles of concurrent engineering and robust design, and offers benefits to the logistics community. The specification of reliability in terms of FFOP offers a sound basis for contracting for equipment reliability, with a design process which is fully traceable and auditable. Once the detailed systems design accept the FFOP, it becomes realistic to talk in terms of a maintenance free operating period (MFOP) for a complete aircraft. The MFOP being defined as a period of operation during which the aircraft should be able to carry out all its assigned missions, without the operating being restricted in any way due to system faults or limitations, with the minimum of maintenance. During the MFOP, therefore, there should be no requirement for any corrective maintenance to the equipment, although action to recover accidental damage from birdstrikes, for example, may be required. During the MFOP the only maintenance activity should be flight servicing, refuelling and re-roling (including weapon loading). All other maintenance, including scheduled maintenance, out-of-phase maintenance and condition-based maintenance will define the MFOP and the associated Maintenance Recovery Periods (MRPs). The MRP downtime would be used to recover the aircraft, system or equipment to its fully serviceable state. The maintenance actions in the MRP would vary according the lifting policy specified for each system and the preventative work necessary to ensure another subsequent MFOP. Ideally any anticipation of an MRP should not waste the useful life of any item but there may be times when this will occur or at least an inspection or overhaul may need to be anticipated.

To adopt this new approach of MFOPs/MRPs, designers will, in future, have to consider many different approaches to providing FFOPs which may involve, for example, graceful degradation of performance without the loss of the mission. The need for improved condition monitoring and the use of the emerging technologies, such as smart structures, will need to be carefully considered. However, major design improvements need to be part of a coherent strategy to examine the trade-offs in terms of overall mission reliability versus the affordability and LCC.

Conclusion

To achieve fundamental changes in the approach to design and drive down life-cycle costs, there must be a greater awareness in industry of a customer's LCC but on the other hand the customer must be prepared to invest in the initial trade-off studies. The aim is to increase the uptime (MFOP) and reduce the downtime (MRP) thereby achieving maximum benefit for the fleet operators. The focus for the improvement of reliability in military hardware must come about from the harmonisation of R&D efforts (industrial, military and academic) and concentration on the main cost drivers in the overall life cycle.

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Ageing Aircraft

Sam G. Sampath

Ageing Aircraft

Ageing Aircraft concerns have dramatically escalated in military and civilian quarters alike during the past few years. The percentage of aircraft that are being operated beyond their design lives is ever increasing. As of 1993, approximately 51% of the aircraft fleet in the US Air Force (USAF) was over 15 years old and 44% was over 20 years old. Yet, some aircraft models that have already served NATO for 30 years or more may need to be retained for another two decades. Due to NATO's changing role which includes peace keeping missions remote from home bases, the requirement of unimpaired high operational capacity, higher utilisation of its air fleets, and budgetary stringency's, prospects are for ageing aircraft problems to continue to become more acute.

Ageing Aircraft has several connotations. Among them: (a) technological obsolescence, (b) system upgradement, (c) changing mission requirements unanticipated during design specification and development, (d) the spectre of runaway maintenance costs, (e) decreased safety, (f) impairment of fleet readiness, (g) unavailability of home depot facilities. If there is one common denominator among these connotations it is that the cost of operating ageing aircraft can be very high. However, technical solutions will be available to fleet managers to deal with the problem of ageing aircraft in 2020.

The aspect of maintaining ageing aircraft cannot be overstated. For instance, on an average, the man-hours required for scheduled, depot-level inspection and repair of the EF-111A aircraft has risen from about 2200 hours in 1985 to about 8000 hours today. In 1985, structure-related maintenance accounted for some 20% of the total man-hours, but today that figure has risen to almost 50%.

Substantial cost-savings in refurbishing ageing aircraft can be realised through application of advanced technologies. For example, in the T-38 aircraft, the originally designed spar of the T-38's wing has been cracking around 2500 flight hours when the aircraft is flown as lead-in fighter role. Cost savings of the order of 40% have been realised through technology insertion involving a newer material. Also, the support requirement for the new option is projected to be the same as for the original design, meaning that no new labour skills will be entailed by the advanced technology option. Thus, newer technology can offer enhanced fleet readiness as a collateral benefit.

Bonded repair of airframe structure has been prevalent practice in the military, with an impressive body of data indicating that bonded boron-epoxy repair patches are effective from the standpoint of damage tolerance and maintenance costs. They are also suited to performing rapid repair in the field. The major obstacle to wider adoption of bonded composite repair is a historic lack of confidence in bond integrity and a lack of experience among the user community. To conform with regulations, damage tolerance of bonded repairs and their resistance to corrosive environments also has to be proven through coupon specimen tests, component tests in the laboratory, and in-flight performance monitoring. User-friendly surface preparation protocol, techniques for consistent and accelerated curing of the adhesive bond, and shelf-life limits for the adhesive(s) need to be established.

Structural joints, including lap-splices, are especially prone to fatigue cracking. Should a need for refurbishment of fastener holes arise, certain methods for enhancing fatigue resistance that have been proposed, cold-working or laser-shock processing for example, could be attractive and adjuncts to life extension schemes. However, their performance with respect to skin thickness, stress corrosion cracking, crack propagation needs to be systematically validated.

The USAF implemented the idea of proof testing in dealing with structural problems in its F-111 fleet. Since then, the method has rarely been used to assure continued airworthiness; however, it is possible that application of periodic proof pressure loads may be an advantageous method for extending the life of certain structural assemblies if they are applied during the early years. Some data appear to idea credence to the idea but a systematic study has not been performed.

Evidence of widespread fatigue damage (variously termed as WFD or multiple-site damage), a form of structural degradation due to fatigue, characterised by small cracks that emanate from adjoining fastener holes and which are difficult to detect due to their size, have been found in some high time airplanes, both military and civil. While only one accident involving a commercial aircraft is attributable to WFD, it poses an immediate threat to structural safety and continued airworthiness, thus entailing huge refurbishment cost - as was the case with the C-141 fleet in the United States. Various components of the airframe (fuselage, aft-pressure bulkhead, domes and bulkhead attachments, chordwise wing splices, wing-fuselage attachments, etc) are susceptible to WFD as the airplane ages, yet a sufficiently accurate methodology to carry out an evaluation of when WFD can be expected to occur does not exist but will be available before 2020. In a few cases, experience has shown that full-scale fatigue tests of components

failed to duplicate multiple-site damage (widespread fatigue damage) that was encountered during service.

The following technical requirements will need to be met for the development of a design methodology to preclude occurrence of widespread fatigue damage during the operational life of an airplane.

a. Date pertaining to occurrences of widespread fatigue damage will need to be collected and catalogued in reference to details of the structural design. The data base will need to reflect the statistical distributions of scatter in values of the design variables corresponding to those to be found in airplane models in the fleet. Data from sub-scale specimens, component tests, full-scale tests, service experiences, and teardown will need to be within the purview of the data gathering effort.

b. An understanding of the mechanics of interaction between discrete source damage (as could be caused in battle) and widespread fatigue damage based on model specimens and full-scale test results needs to be developed. Specifically, a criterion, or a set of criteria, is required to predict the linkup of cracks characterising discrete source damage and widespread fatigue damage, when the structure is subjected to static and fatigue loading. The effects of the geometrical and configuration features and the mechanical properties of the structure, on the formation and progression of multiple-site damage will need to be identified. The role of a crack arrester in containing a fracture - thereby preventing structural failure - when widespread fatigue damage is present in its vicinity, is to be established as a function of fastening detail and arrester stiffness.

c. A calculation scheme, validated by data pertinent to occurrence of widespread fatigue damage, is needed to forecast the time when widespread fatigue damage is likely to set in under fleet operating conditions. Such a methodology can also be used to define the design corridor that will avoid or postpone the possibility of widespread fatigue damage. Risk analysis models will be within the scope of such an effort. In addition, it will support multiple-lifetime, full-scale fatigue testing - which are necessary but very expensive to perform - to minimise the occurrence of widespread fatigue damage, by providing coefficients to correlate data from sub-scale and component tests and analytical schemes with the results to be expected from full-scale tests. In addition to fatigue, the methodology will need to consider, if warranted, the roles of corrosion and fretting in promoting widespread fatigue damage.

It is generally agreed that repair of flight safety critical components of an airplane can affect its structural integrity; in particular, the design of riveted repairs need to protect the fleet from the debilitating effects of WFD. Multiple repair patches in close proximity's, which are not uncommon, heighten such a concern. Since it is axiomatic that a structural repair causes the stresses around it to redistribute, the possibility of a repair degrading the damage tolerance characteristics of the assembly, even at locations somewhat removed from the area of repair, always exists, as the US Air Force has experienced. Development of a comprehensive, user-friendly software to help design and fabricate repairs, including field repairs, should be pursued.

Corrosion is the bane of ageing aircraft structures and accounts for a large fraction of maintenance hours and cost. Time after time, fleet surveys of ageing airplane structures have shown corrosion to be the most frequent finding. Technology insertion through materials with improved resistance against corrosion, stress corrosion cracking, and corrosion-fatigue, has the potential for huge payoffs, as demonstrated in the C-5 and the C-130 fleets.

It is significant that thickness loss due to corrosion to the extent of 10% is allowed but the limit is based on static strength consideration, not fatigue resistance. More importantly, in the field, the identification and removal of such amounts of corrosion is based on visual means, whereas laboratory test data indicate that minute amounts of corrosion that may form at the base of a crack, perhaps even at the microscopic level in the material, will profoundly accelerate corrosion and crack-growth rate. Thus, the interaction between corrosion and fatigue, which typically is not taken into account, may be important from the point of inspection threshold, inspection frequency, residual strength and fail-safety. However, a balanced perspective will include the observation that corrosion is more an economic problem, less a safety issue.

The effect of corrosion on a fatigue and static strength as a function of different species of corrosion commonly found in air-frames and engine components will need to be quantified through a taxonomic data gathering exercise. Corrosion prevention and corrosion control schedules are integral and important parts of every aircraft maintenance program. Environmental regulations will increasingly necessitate dephasing of current generation of corrosion inhibitors and products for paint removal and surface cleaning, and require development and qualification of alternatives which also avoid retrogression of fatigue related properties of the treated material. "Apply and forget" type of schemes for passive corrosion control, such as ion implantation, are good candidates for research support.

Some recent instances, a few having led to unfortunate consequences, have highlighted the need for new non-destructive techniques and procedures

and airframe and engine inspection (NDI) that are demonstrably superior in terms of their figures of merit (reliability, user-friendliness, cost, ruggedness and throughput) to those in current usage. Technology advancement should be aimed towards detection of hidden corrosion and cracking in secondary (visually uninspectable) layers, inspection of inaccessible locations, techniques with wide field-of-view that can be used to scan relatively wide areas, techniques that discriminate between disbonds, weak bonds, and corrosion, and development of robust and affordable NDI systems that can also be easily adopted by for field usage. Although non-destructive methods, such as x-ray radiography, low or high frequency eddy current, dye penetrate and so on, are used to periodically inspect airplane components, by far, the biggest pay-off will result from improvement in visual inspection reliability on account of its being the preferred inspection method. Thus, development of aids to enhance visual acuity should be a research priority. Dictated by aerial reconnaissance and underwater detection needs of the military, recent years have witnessed significant developments in sensor technology - infrared and acoustic sensors in particular which appear to be highly promising candidates for NDI applications in the aerospace industry. The state-of-the-art with respect to several other methods (laser holography/shearography, magneto-optics, ultrasonics, etc) make them highly prospective as well. Apart from their capability to rapidly scan large areas of the fuselage, wings and other control surfaces for determining the presence of cracks, corrosion or disbonds, they appear to be superior to more conventional methods in terms of reliability. Tight cracks, dirty surfaces, cracks or other types of flaws having irregular features, paint layers, tool marks, etc all impair inspection reliability, thus degrading human interpretative skills. Noise suppression through sophisticated filtering algorithms, signal amplification, imaging are techniques that effectively enhance audio and visual discrimination. In recent years military applications have led to technological break-through relating to signal processing and pattern recognition schemes have been achieved. Such developments offer significant potential for conductive use with emerging NDI equipment and techniques. Use of robotic devices also offers the prospect of substantial improvement of human performance during inspection. Tasks involving repetitive inspection or inspection of inaccessible areas or engine rotating parts are prime candidates for the application of robotics. Development of a facility that offers test-bed facilities, resembling typical aircraft maintenance facilities, for prototype development and validation is a logical route for laboratory research on NDI to result in prototype design and production of equipment that industry can field. Such a centre should also serve to screen NDI candidate technologies in terms of their cost-benefit induces. Alternate methods for compliance with mandated inspections can be validated. The collection of an inventory of structural assemblies and components that comprehensively describe the accessibility, specificity, and geometrical and material features of the structural components to be inspected in a typical maintenance facility is a research issue. Associated with that issue is the task of creating surrogates or analogues with the appropriate defect demographics.

The reliability of the inspection methods used by the aircraft industry to detect flaws in the structure, in conjunction with estimates of the rate of structural degradation due to fatigue, corrosion, etc., is used to determine when and how frequently the structure needs to be inspected. It has been shown that the rigors exerted on the inspection system by the environment in an aircraft maintenance facility, significantly affect inspection reliability. Conversely, data obtained under carefully controlled conditions over-estimate the probability of detection of a given defect size and, hence, lead to unconservative values for inspection frequencies. Yet, there is an acute dearth of data that reflect inspection reliability associated with a variety of inspection tasks encountered in a maintenance hanger. Also, acceptance of newer NDI technologies will be conditional on their demonstrable reliability.

In gathering reliability data corresponding to visual or other NDI inspection methodologies, the sensitivity of the variables characterising an inspection station to the outcomes from the data gathering exercises can be used to identify the factors that positively or adversely favour human performance. Such data will be invaluable for designing, or making improvements to, maintenance facilities.

An obvious target for increased maintenance reliability is the wide variation in typical NDI inspector performance observed in several studies and through analysis of field data. Previous studies show inspector proficiency as key to high inspection reliability and that proficiency and periodic training are directly correctable. Adoption of a set of proficiency standards should stress not only the physiological aspects, like visual acuity but also refer to newer methods of construction and newer NDI technologies. Thus, a set of syllabus that define proficiency standards is a first requirement.

Fleet reliability and safety is monitored through gathering and analysing reports about defects, malfunctions and failures of systems and subsystems. In this regard a decision support system based on risk analysis of safety-critical performance indicators would be helpful. Development of performance indicators, embedded in software systems, that encompass particulars about aircraft design, aircraft maintenance, mission requirement and discrepancy reports, whose thresholds are self-adjusted through intelligent tutoring algorithms will be required.

Ageing Engines

Jean-Pierre Immarigeon

Ageing Engines

Because of the high acquisition cost of military aircraft and the diminishing resources for new equipment acquisitions, many aircraft from NATO nations are likely to be kept in service longer than originally intended. The task of achieving life extension while ensuring the high levels of safety and reliability established in the past, will present formidable challenges.

From the time an aircraft is put in service, components from both the airframe and engine(s), undergo a process of damage accumulation which may take may forms and is influenced by usage severity. The long terms effects of service induced damage are not always well understood, nor are they well documented, particularly for high time vehicles. The damage can affect both the performance and structural integrity of airframe and engine components. Designers and operators alike need to take into consideration this ageing process for ensuring continued safety and reliability of the vehicles.

The ageing process for engines is quite different from all affecting the airframes. Engines tend to age in more varied ways, and do so at considerably faster rates. Some components, and in particular gas path and other hot section components, incur many forms of damage, depending on the component type, engine type, usage severity and operating environment. Among these components are highly critical rotating parts, such as discs, that strongly influence the safety of the aircraft.

For gas path components, such as compressor and turbine blades or vanes, the damage can be external, affecting surface finish or dimensions, which tends to adversely affect aerodynamic performance and/or load bearing capacity. This type of degradation may occur for instance as a result of erosion, corrosion, hot corrosion or high temperature oxidation. For hot parts, and parts subjected to cyclic mechanical loads, damage may also be internal, in the form of creep, fatigue or thermomechanical fatigue damage, and may involve cracking, as a result of which structural integrity of the parts may be compromised. Extended usage may also lead to high cycle fretting-fatigue wear of blade dovetail regions and disc dovetail slots. In addition, compressor and turbine discs, including associated structural hardware such as spacers and cooling plates, may also develop creep-fatigue cracks at various fracture critical locations.

The rates of damage accumulation are much faster in engines, as compared to airframes. This is because the operating environment is generally more demanding for engine components. In addition to cyclic mechanical loads, as experienced by airframe components, engine parts are subjected to simultaneous thermal and chemical loads. The combined effects of these external loads can greatly accelerate the ageing process. When the damage becomes excessive, the parts are replaced with new ones. The replacement of service damaged parts, addicted by design or established by inspection, is costly to operators.

To safely and reliably predict the useful life of components, one needs an accurate knowledge of the stresses and temperatures in the parts, as well as their variation with time. One also needs to understand the response of the structural materials to these external forces and the environment, especially in terms of the modes and rates of damage accumulation and their interactions. There are significant uncertainties associated with all these external variables, as well as in the accuracy of the structural analysis methods and methods of damage modelling employed for component life prediction. As a consequence, components often deteriorate at rates much faster than predicted, with the result that premature unforecast failures may occur. Such failures affect powerplant reliability, which in turn has a significant impact on aircraft operational cost and capabilities.

These uncertainties and related risks provide strong incentives to identify strategies for ensuring continued safety, reliability and maintainability of ageing engine fleets. In this context, future R&D efforts should be directed towards:

- i Developing more accurate methods to measure service stresses and temperatures in engines on a component basis and as a function of time for accurate mission definition,
- ii Improving our understanding of damage accumulation in engine components, with particular emphasis on expensive to replace components,
- iii Improving the accuracy of structural analysis methods and algorithms used for component life prediction,
- iv Developing improved and more reliable techniques for inspecting damaged components non destructively,
- v Applying fracture mechanics based life prediction methodologies for critical components, across NATO engine fleets.

Furthermore, there is evidence to show that the high cost of replacing damaged components in engines is a significant factor in the overall life cycle cost of aircraft. This provides incentives to search for advanced materials and processes that are capable of prolonging engine components lives. Future R&D effort on component life extension should be focused on:

i Development of new materials with increased damage tolerance,

ii Development of coatings or other forms of surface modification treatment to provide increased protection against environmental attack, abrasive wear, fretting fatigue or other modes of surface degradation,

iii Introduction of novel rework techniques, such as advanced repairs or rejuvenation heat treatments, to return excessively damaged parts to functional serviceability.

The availability of more accurate life prediction methods would allow the use of less conservative design factors, while insertion of more durable materials and advanced rework procedures would allow component lives to be extended beyond current limits, thereby leading to reductions in the operating costs of the NATO aero engine fleets.

Smart Structures and Materials in Aerospace Applications of Next Generation

Christian Boller

Introduction

Development in disciplines such as sensing technology, computation, control, micromechanics, materials including processing and many others has made significant progress during the past decades. This progress has been mainly possible through an in-depth analysis of the different aspects in these disciplines. To consequently take more advantage of this progress a synergy between these different disciplines has to be established, resulting in what has been termed to be smart materials and structures. Smart (alternatively; active, adaptive, multifunctional or intelligent) materials and structures is - briefly explained - the integration of sensing and actuation elements into a structure or even more ambitiously into a material, with sensor actuator being linked by a controller. Materials actually favoured for integration include optical fibres and piezoelectric materials with respect to sensors, piezoelectric/electrostrictive materials, shape memory alloys and electro-rheological fluids with respect to actuators and microprocessors, neural networks, fuzzy logic and various types of signal processing with respect to control. Since performance of aircraft and spacecraft has progressed in a sequence of steps in the past, smart materials and structures technology can thus be considered to be a next step in enhancement.

The Way To Smart Materials And Structures

It is now more than a decade ago since people have started to talk about smart materials and structures. Various definitions have been given (e.g., Ahmad 1988, Takagi 1989, Measures 1989) and various expressions such as intelligent, multifunctional or adaptive are used, which sometimes need to be clarified. There is however some common sense in the way that a smart material or system incorporates sensors and actuators with both being linked via a controller. Trying to summarise the various definitions and expressions can result in a view as shown in Figure 1.

A key question leading to smart materials and systems is: *Why cannot materials and systems with structural functions take over additional functions?* Their basic/traditional use is mainly related to passive functionality. It is therefore termed to be a *passive material or structure.* Adding sensors to the material or structure leads to what can be called a *sensory material or structure.* The term *active material or structure* can be used if the material or structure also includes actuators. Sophistication is improved if sensors and actuators are linked via a controller allowing the material or system to adapt itself to various prescribed conditions which can be called an *adaptive material or structure.* The highest level that can be actually though of is achieved when the adaptive material or system also includes a processor allowing itself to adapt to various conditions by self-learning. It can be specified to be the real *intelligent material or structure* and is in many cases a vision which still requires to be achieved.

A look into specific books, journals and conference proceedings shows that the wide range from sensory to intelligent materials and systems is covered under the expression of smart, adaptive or intelligent

	Sensor	Actuator	Controller	Processor
Intelligent Material and Structure	•	•	•	•
Adaptive Material and Structure	•	•	•	
Active Material and Structure	•	•		
Sensory Material and Structure	•			
Passive Material and Structure				

Figure 1: Smart Materials and Structures - Definitions and Expressions

materials and structures. Technologies considered are not limited very much although there are some materials and technologies being actually favoured. These include optical fibers and piezoelectric and electrostrictive materials, shape memory alloys (SMAs) or electro-rheological (ER) fluids with respect to actuators and microprocessors, neural networks, fuzzy logic and various types of signal analysis with respect to control.

Activities in the world of smart materials and structures have mainly originated from applications in aerospace and have been published in a variety of conference proceedings and papers in journals. A first workshop on "Smart Materials, Structures and Mathematical Issues" was presented at the US Army Research Office in 1988 (Editor: C.A. Rogers, 1988). In 1992 AGARD's Structures and Materials Panel organised a meeting on "Smart Structures for Aircraft and Spacecraft" (AGARD 1992) which has possibly been one of the first conferences on smart structures being fully related to aerospace. In 1994 the American Institute for Aeronautics and Astronauts (AIAA) then performed another conference on 'Adaptive Structures' (AIAA, 1994), which was also solely related to aerospace.

Another conference being very much related to aerospace is the International (originally US/Japan) Conference on Adaptive Structures (ICAST, 1991 - 1995), which was established in 1991 and has been held since every year.

Other conferences where smart structures applications for aerospace are partially presented include the annual 'Fiber Optic Smart Structures and Skins' (SPIE, 1988 ff) organised by SPIE since 1988, the annual 'Adaptive Structures and Materials Conference' and the biannual 'European Conference on Smart Structures and Materials' both being held since 1992.

A lot of motivation has been spread through the ideas generated and successfully realised for aerospace applications (eg., Crawley and Anderson, 1989, Wada and Garba 1992, Fanson 1993). In the meantime applications are also considered with respect to military and civil transportation, starting with those for military aircraft and recently followed by those for automobiles and railway systems. This development becomes especially obvious when considering a wider range of sensor, actuator and control types than those mentioned before. Other types of sensors can be those based on the change of electrical properties such as receptivity or capacity, thermal imaging or pressure. Actuators mainly used today are electrical motor, hydraulic or pneumatic actuators. These different types of sensors and actuators linked via control are the basis of advanced engineering systems actually available in products which easily fall into the range of smart/intelligent structures.

The sensing and actuation materials considered and mentioned before cannot be specified to be new anymore. Nor can this be said with respect to phototropic or electrochromatic glasses. It is more the challenge to combine these materials with conventional structural materials such as can be well done with polymer based composites Varadan and Varadan, 1993) or by introducing these materials into a wider industrial application. Another significant area being still exclusively related to research is the implementation or sensing and actuation functions on a microstructure or even molecular basis into a material (Shinya 1994; Hirukawa 1994; Takeuchi 1994).

Whenever the application of smart materials in engineering structures is considered, the following question has to be answered.

How has a smart structure to be designed to become cost-effective?

Answering this question can be done by using analytic approaches easily determine the boundary conditions of smart materials, followed by a study using cost analysis procedures.

Examples Of Available Systems And Materials

When comparing the definition given above for a sensory, active, adaptive and intelligent or briefly a smart material or structure with materials systems used today in military aircraft, it becomes obvious that smart structures have already been implemented somehow. Aircraft nowadays all contain a large number of sensors such as for sensing temperature, speed, acceleration, brightness, humidity, volume flow or electromagnetic signals or actuators allowing to move components, to exert forces, to inject a fluid or a gas or to reduce light intensity. All actuation is done by either human or electronic control, the latter requiring the type of sensors mentioned before. The smart structures available today are based on the fact that structural components are fully made out of passive materials with sensors and actuators being added to the system. They can be classified in the range from sensory to adaptive structures, while intelligent structures are still the vision to be followed in future research and development.

Based on the idea that smart structures and materials are considered to be the next step in enhancing the performance of aircraft and spacecraft, a variety of major initiatives have been generated such as the space activities at NASA-JPL (eg., Controls and Structures Interaction (CSI) program. Precision Segmented Reflector (PSR) program etc), the US Air Force smart structures program, SDI or research and development programs going on in the area of adaptive wings (NASA/Lockheed,

DASA/DLR/Daimler-Benz, BAe/Dowty) or in damage monitoring (eg., the USAF Wright Laboratory Smart Metallic Structures Program and its relation to the USAF Aircraft Structural Integrity Program ASIP).

Although there is a variety of sensors, actuators and control algorithms already available in military aircraft today, it is far beyond the scope of this paper to present all available systems and their possible relation to smart structures. In a few papers (Agnes and Silva, 1992; Schmidt and Boller, 1992) major potential areas for applying smart structures in military aircraft have been identified, which in both papers turned out to be the following three:

- Air health and usage monitoring, which is a sensory system mainly related to identification and possibly validation of damage in structures;
- Active and adaptive structures which is related to shape control, vibration damping and light transitivity of structural components, using materials with sensing and actuation capabilities such as piezoelectric, SMAs, ER fluids or electrochromatic glasses;
- Smart skins, being load carrying structural elements with integrated avionics (antennae), which can be either a sensory, active, adaptive or even intelligent structure depending upon its terms of use.

Regarding the kind of materials considered to be smart, piezoelectric, SMAs and electrochromatic glasses are the ones already being used today. So far their application is limited to their traditional use such as sensors and often simply controlled actuators within the structures described below.

Sensory Structures

In aerospace condition monitoring is widely used in jet engines. A network of sensors monitors temperature and gas glow within the engine and thus informs if critical engine parameters are within the operational range. Integrated health and usage monitoring system (IHUMS) have become quite popular with helicopters and have been recently made commercially available for helicopters (Bristow, 1992). These systems have been made to monitor gears and are based on sensors monitoring acoustic signals being generated from the various rotating parts of the gear. Other systems include the use of video cameras for monitoring flaps and landing ear positions of widebody aircraft or the ones used for monitoring operational loads of military and civil aircraft based on either strain or flight parameters, where a broad selection of systems has been described (AGARD, 1991).

Another important area related to sensory structures is smart skins. They are designed for control of aerospace structures such as acoustic noise and vibration drag and skin friction using advanced polymeric smart materials, MEMS (Microelectro-mechanical Systems) and built-in antennas (Varadan and Varadan, 1993). The objective is to develop something being denoted as "smart wall papers". Applications include smart helicopter rotorblades with microstrip patch antennas and detection and discrimination of hostile threats resulting from laser, radio-frequency and x-rays such as having been performed in the satellite attack warning and assessment flight experiment (SAWAFE) for actively filtered transparencies and conformal antennae (Obal et al, 1992). Wireless remote and continuous telemetry for application to rotorcraft and smart skin aerospace structures are further areas discussed (Varadan and Varadan, 1994).

Active Structures

De-icing systems such as used on leading edges of aircraft wings and on aircraft engines are a type of active structures widely known. They consist of a pressure of ultrasonic sensor and pneumatic or electrical heating actuation system.

Electrochromatic windows allowing to change light transitivity is another active structure considered for windows of aircraft cockpits (Daimler-Benz, High Tech Report, 3/1994). The window has a sandwiched cross-section including two transparent electrodes, two electrochromatic layers and an electrolytic polymer layer. A small current of 1 to 2 volts imposed by the electrodes on the system allows to change the colour of the electrochromatic layers as a result of a chemical process initiated by the electrical current.

Adaptive Structure

A type of adaptive structure being widely known is the autopilot systems used for navigation and control of aircraft.

Noise cancellation in aircraft fuselages is a major issue with turboprops. Noise is monitored at the locations where it should be cancelled using conventional microphones. The signals are analysed and processed for actively generating an anti-noise which is either emitted using conventional loudspeakers or recently by adapting some small piezoelectric plates to the inside panel of the fuselage (Fuller et al, 1992).

A major initiative has come from space applications. Various activities performed have been related to space station freedom remote and space crane manipulator system, space based radar, the main truss, active vibration isolation of stores, equipment,

sensors or pods. A lot of knowledge has been generated through the USAF Advanced Control Technology Experiment (ACTEX) for demonstrating active vibration suppression in space vehicle applications using embedded piezoceramic actuators in a smart strut (Das et al, 1992). Truss structures with in-line sensor/actuator systems for active damping and possibly even vibration suppression, which can be individually controlled in a space truss work, has been a major result of this and other programs (Wada and Garba, 1992). Other types of piezoceramic actuators have been developed allowing to avoid sensor (eg., interferometer) jitter resulting from systems such as cryocoolers or solar array panels in space vehicles. These different kinds of active elements have allowed to develop concepts for performing in-orbit modal analysis of large space structures or on active vibration damping of a space based radar. Disturbance isolation, active vibration suppression and active optical pathlength compensation of telescopes and optical interferometers have been successfully used with the Articulating Fold Mirror (AFM) which forms part of the optical scheme for correcting the spherical aberration of the Hubble Space Telescope and in other fields (Fanson 1993). Each ATM utilises six electrostrictive multi-layer ceramic actuators which also contain the required sensor unit while control is performed for the ix actuators in a central unit. Adaptive structures for in-space assembly is another area of consideration.

Concepts, feasibility studies and wind-tunnel demonstrations for the control of aeroelastic response using smart structures in fixed and rotary wing aircraft applications have been performed. These include controlled transonic drag and tail buffeting reduction as well as active wing and panel flutter control and minimisation/suppression using active means such as an active plan or others. Decoupling of gyros from elastic aircraft vibration modes, helicopter rotor blade vibration suppression and control, and skin panel fatigue life extension are other areas widely discussed. Active landing-gears have been proposed for the ride comfort Catt et al, 1992).

With respect to missiles gun-fire vibration reduction and active spoiler control are aspects to be mentioned.

Future Trends

A trial to summarise state-of-the-art and future trends in technological development of smart materials and structures is shown in Figure 2.

The following three main areas are seen to actually drive the technological development:

1. Engineering structures made of passive materials with sensors, actuators and controllers being added (attached) to the system in the way described before.

2. Data processing and control which mainly involves high performance computing, neural networks, fuzzy logic and generic algorithms as well as microelectronics related to it.

3. Materials and micromechanics which includes all kinds of materials and components such as fibre optics, piezoelectrics, SMAs and polymers, ER-fluids, nanostructures, composite materials, liga and silicon technology.

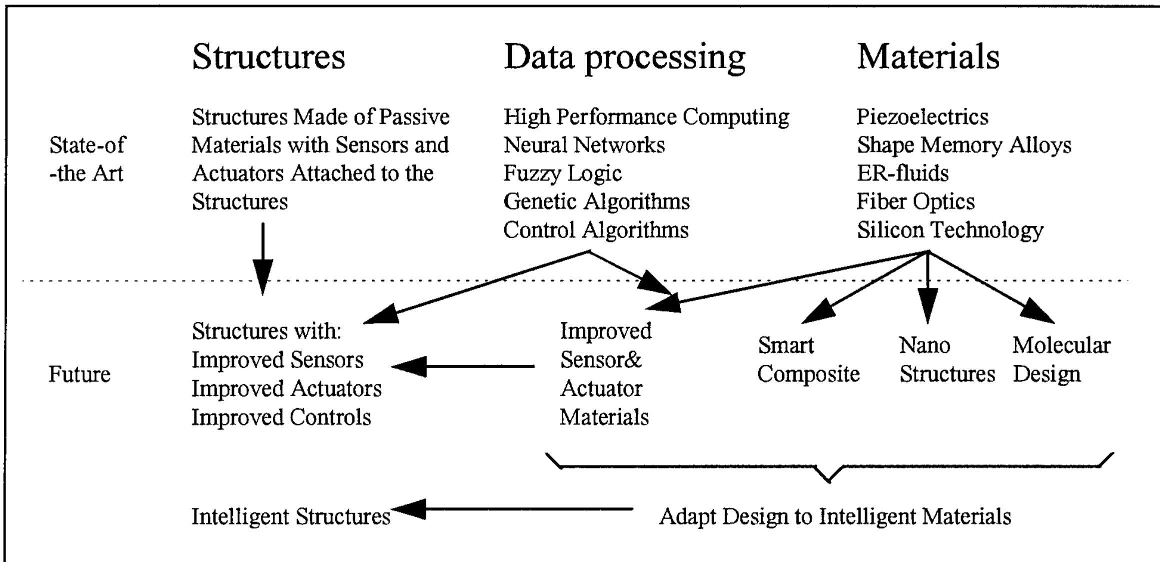

Figure 2: State-of-the-Art and Future Trends in Smart Structures and Materials

With respect to the first area progress can be expected through improvement of the sensors, actuators, and control algorithms used. Improvements achieved in the second area are applied for increase of the performance and/or the number of sensors and actuators used in the smart structure. Sensors and actuators can still be monofunctional and just attached to the structure considered.

The third area can again be split into three sections. The first section is related to improvement and possible development of materials with sensing and actuation functions. This includes topics such as improved ductility of piezoceramics, increase of piezoelectric induced strain as well as development of means for stroke amplification, higher Curie temperatures with piezoelectric polymers, better understanding of the constitutive behaviour of SMAs with respect to control of SMA actuation, extension of the range of possible transformation temperatures is SMAs, and much more.

The use of composite materials, which is related to the second section, has opened a wide field for integrating functional elements into these materials. This includes the integration of sensing or actuation elements such as fibre optics, piezoelectrics or SMAs. Studies recently performed involve determination of the effectiveness of these composite materials with respect to strength and performance. A lot of ideas have been generated in that area by integrating various types of sensors and actuators using technologies such as applied for printing electric circuit boards or other types of surface coating, thus leading to what is called a conformal smart skin (Varadan and Varadan, 1993). Since such a type of composite will be able to take over sensing and actuation functions on a macroscopic and microscopic level, significant changes in design philosophies can be expected. However these new structural components have to meet the requirements set with respect to strength, environmental stability, cost and reliability, the latter being achieved through redundancy in sending and actuation elements allowing graceful degradation during operation. Activities similar to what is performed with smart composites is starting on a microscopic level in metallic and polymerbased materials through implementation of particles with sensing and/or actuating functions in a way as having been initiated with the development of nanostructures. Finally it is worth mentioning that work is in progress trying to implement sensing and actuation functions on a molecular basis in polymers.

The third section can be related to work performed with respect to micromechanics including micromachines. Work performed here is mainly related to electronic, medical and surgical applications and has still not gained significance for being directly applied in transportation vehicles.

Analysing specific scientific papers leads to the conclusion, that smart materials and systems are mainly considered to be used in transportation vehicles for the following:

- Monitoring the condition of a system/structure or the environment (situation awareness);
- Exerting strokes and forces;
- Influencing dynamic behaviour.

Condition monitoring has become a major issue with composite materials where major concern exists with respect to barely visible impact damage (BVID) which occurs inside the structural material and can often not be seen from the outside. To minimise the effort required for inspecting the material or component with conventional Non Destructive Testing (NDT) technology, the NDT-technology is considered to become an integral part of the structure by implementing a network of appropriate sensors (Boller and Dilger, 1992). The types of sensors mainly considered are fibre optics (Measures, 1992; Tutton and Underwood, 1992) and piezoelectrics (Boller, 1994). Such structure health monitoring systems are actually mainly discussed for aircraft applications but could even gain interest when especially carbon fibre reinforced polymers will be more applied in railway systems and automobiles. Other issues include monitoring any condition which is required as an input for an adaptive or intelligent structure (eg., monitoring the pressure profile for an adaptive wing).

Exerting strokes is done to statically change the position of a component. A lot of effort is actually placed on adaptation of the shape of aerodynamic profiles according to varying service conditions. When deformation speed is relatively low but strokes quite high, the use of SMAs is a solution to be considered (eg., Misra et al, 1992). However this requires a precise control of temperature, which can become highly challenging when thinking of operational temperatures ranging between -50 and + 120°C for aircraft applications. If deformation speed is a major requirement, piezoelectric actuators seem to be a considerable solution. A lot of studies have been performed with respect to active control of helicopter rotor blades using induced strain actuators where overviews have been given by Crawley and Anderson, 1989. Strehlow and Rapp, 1992, Barrett, 1995, or Giurgiutiu et al, 1995. It turns out that a hinged flap activated by a dimorph PZT actuator such as proposed by Spangler and Hall, 1989 is the most promising solution so far, especially since improvement has been gained with that system during the last years. Comparing this to conventional helicopter rotorblade design shows that the potential of active, adaptive and intelligent materials can only be taken full advantage of when

design is adapted to the potential of these materials, which has been especially done here. Looking to applications in engines, control of valves using piezoelectric stack actuators seems to be an interesting field.

Reducing dynamic loads in any kind of engineering structures is a major field for considering intelligent materials and systems. Solutions have been proposed such as using piezoelectric stack actuators as part of an active acoustic noise control system between a jet engine and the fuselage (Sumali and Cudney, 1994).

To achieve large displacements required to reduce vibrations of relatively low frequency, much effort has to be placed into the activities of amplifying the low displacements generated by the piezoelectric actuators. Alternatives for these applications may exist by using other types of actuators such as based on ER-fluids (Naem et al, 1994).

Much effort is actually also going on in aeroelastic research using piezoelectric actuators for flutter and buffeting suppression and vibration damping (Heeg et al 1994). Solutions here consider piezoelectric patches integrated into the aerodynamic profile, allowing to globally as well as locally influencing the aeroelastic and aerodynamic behaviour. Finally the noise cancellation methods based on integrating piezoelectric patches into panels such as mentioned above is another activity in the field of reducing dynamic loads.

Based on the experience gathered so far with smart structures and materials, future needs have been expressed in various publications (eg., Crawley, 1992, Agnes and Silva, 1992), which can be summarised as follows:

Sensors: There is still a great deal of work to be done with respect to design and optimisation of sensors in the way that sensors can be tailored according to the specific needs they will be used for. One of these needs is monitoring of nonuniformly propagating acoustic signals in nonisotropic materials and the requirement for characterising this for a range of layups structural components will be made of. Furthermore it would be desirable to distinguish between fibre and matrix cracking which would then allow to determine residual strength. Whenever this will be solved, sensing systems have to achieve a higher robustness, requiring some absolute or reference capability and not being completely relative.

Actuators: Based on commercially available actuation materials today (eg., piezoelectric and electrostrictive) strain has to be increased by a factor of 3 to 10. Shape memory alloys show a good performance with respect to strain but their bandwidth in response time, constitutive behaviour, and others still need to be improved if ever a larger variety of applications is considered. Actuators on the basis of complex electrode patterns is an interesting possibility for increasing piezoelectric strain, but much more needs to be studied to understand the actuation, electrode, and host material interaction and thus the actuator's performance. Only if these actuation power improvements will be realised, benefits can be expected from systems such as considered for active flutter control.

Control: Aerospace systems mainly require non-linear adaptive controllers, which have to be based on real-time computing, miniaturised and of large bandwidth. Most of the control has been done on a mainly theoretical basis and for the control of discretised systems. Discretisation is however not appropriate in a structural component, which therefore requires new ways of control. Distribution of control and definition of the various levels of control is another major issue to be considered.

Design: Since sensors and actuators are an integral part of a structural component, power conditioning and switching becomes important with respect to minimising local heat loads, possibly leading to thermal degradation of the host material. Furthermore the integration of sensor and actuator elements into a structural material and component can significantly influence mass, stiffness and interfere with the load path, thus introducing new structural discontinuities of unknown significance. Another aspect is hermicity of embedded components which points special emphasis on reliably isolating the embedded components from environmentally deteriorating factors. Whenever smart materials and structures will have passed the laboratory stage, service liability, vulnerability to handling and damage, and repair will be of major significance. Before all, technology payoffs must be quantified and requirements established. Only when testing has been done on articles where key issues have been demonstrated understandably, more advanced flight worthy testing will be useful.

Manufacturing: Manufacturing of smart materials and structures is an issue which has not very much been considered before. It includes development of innovative techniques for packaging sensors, actuators and nay other kind of electronics into structural materials and components, which have to become structurally robust in the way that they can survive stresses and strains they will be exposed during their in-service life. This is just one aspect of certainly a large number of others still to be explored.

Conclusion

Summarising state-of-the-art and future trends in smart systems for aerospace applications leads to the conclusion that first applications start by adding

sensors, actuators and controllers to a conventionally designed system based on passive materials. Progress in data processing technology provided today can be made use of at this stage, which mainly allows to increase the number of sensors or sensor information as well as to improve the performance of controllers applied. Parallel to this a large amount of development has to be done in the are of intelligent materials. As long as their potential is not sufficiently described it is difficult to say if they can be used in reality. A look at three different R&D programmes on adaptive aircraft wings in the USA, Germany and the UK respectively proves the conclusion made here to be realistic since they are all based on the following strategy: (1) Take a wing with its conventional sensors and actuators and improve control and data processing which allows to extend the use of existing flaps; (2) implement sensors and actuators based on appropriate materials with known characteristics (eg., piezoelectrics, SMAs, ER-fluids) and start to adapt the structural design according to these materials; (3) Use a smart composite system for design of the wing. It is the latter two steps which strongly require much more knowledge about active, adaptive and intelligent materials than we have today.

This knowledge will be the basis for deciding if these active, adaptive and intelligent materials can be finally applied due to the various requirements they will have to fulfil with respect to strength, environmental stability and compatibility, and especially cost. It is difficult for a material scientist to be aware of these requirements and it might be difficult for a designer in aircraft engineering to clearly understand the potential of new materials developed so far. To overcome this gap, to briefly determine the solution of best technological and economical potential and to always be on the track of minimum development time, ,procedures for validating the technological and economic potential have to be established.

It is advanced data processing, electronics, control, sensing and actuation which will help to let transportation systems of today to become somehow 'smart' tomorrow. It is however the introduction of smart materials which can significantly lead to a change in our engineering design philosophies towards intelligent structures. But none of all this can become reality if cost-effectiveness has not been proven.

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14. Abstract

Volume III, the technical papers supporting the report of the NATO Advisory Group for Aerospace Research and Development (AGARD) study: 'Aerospace 2020'. This study explored the most advanced technologies, relevant to aerospace, being researched and developed in laboratories today. The study focused on the most promising current technologies and the organisational and tactical consequences they will have at the field and system levels, over the course of the next 25 years.

Topics include: a discussion of the impact of proliferation, human-machine interaction, synthetic environments, directed-energy weapons, information technologies, unmanned tactical aircraft, suborbital launchers, hypersonic missiles, and a discussion of affordability issues.

Technologies are assessed from the viewpoints of both potential capabilities and threats. Observations and recommendations are presented.

Volume II contains the conclusions of the report. Volume I is a short summary of these conclusions.

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